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IT Enviroscience
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EVALUATION OF THE UNION CARBIDE PURASIV® HR VAPOR RECOVERY SYSTEM

By

Charles S. Parmele, Harold S. Basdekis, and Michael R. Clark

IT Enviroscience, Inc.
9041 Executive Park Drive
Knoxville, Tennessee 37923

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Project Officer

Ronald J. Turner
Industrial Pollution Control Division
Industrial Environmental Research Laboratory
Cincinnati, Ohio 45268

INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY
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The goal of this study was to perform an engineering evaluation of a new fluidized-bed adsorption technology that was developed in Japan. This technology has been licensed by Union Carbide and is now being marketed in the United States under the name PURASIV HR Vapor Recovery System. Since this technology allows the use of nitrogen to regenerate the carbon, the need for additional steps to separate water-miscible solvents from the water may be reduced.

The engineering evaluation was developed by performing field tests on a full-scale PURASIV HR unit at Polaroid Corporation, Waltham, Massachusetts. These data were supplemented by operating information from a PURASIV HR system at General Motors Corporation, Fremont, California. Capital and operating costs were then developed for both PURASIV HR and fixed-bed adsorption systems. Technical comparisons between the two types of adsorption systems were also made.

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory-Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

The results of an engineering evaluation of a fluidized-bed carbon adsorption technology for a solvent recovery/emission control application are presented herein. The technical and cost comparisons between the fixed-bed and fluidized-bed adsorption systems will aid the government and industry environmental control engineers in selection of the appropriate carbon adsorption device for specific volatile organic emissions.

Additional information on the results of the study may be obtained by contacting:

David G. Stephan
Director
Industrial Environmental Research Laboratory
Cincinnati, OH 45268

ABSTRACT

Vapor-phase carbon adsorption is a versatile and valuable air pollution control technology because it is usually the only nondestructive technique that can effectively and economically remove volatile organic compounds from atmospheric emissions when the exhaust concentrations are below 5,000 to 10,000 ppm. One drawback of the steam regenerated, fixed-bed adsorption technology is the inherent contact of water with the solvents during the regeneration step.

The goal of this task order was to perform an engineering evaluation of a new fluidized-bed adsorption technology that was developed in Japan. This technology has been licensed by Union Carbide and is now being marketed in the United States under the name PURASIV® HR Vapor Recovery System. Since this technology allows the use of nitrogen to regenerate the carbon, the need for additional steps to separate water-miscible solvents from the water may be reduced.

The engineering evaluation was developed by performing field tests on a full-scale PURASIV HR unit at Polaroid Corporation, Waltham, Massachusetts. These data were supplemented by operating information from a PURASIV HR system at General Motors Corporation, Fremont, California. Capital and operating costs were then developed for both PURASIV HR and fixed-bed adsorption systems. Technical comparisons between the two types of adsorption systems were also made.

The PURASIV HR technology can be viable for adsorption applications and can compete economically with fixed-bed systems especially at flow rates above 5,000 scfm when the higher capital costs for the PURASIV HR system can be offset by savings in steam and electricity costs. Neither type of adsorption system should be excluded from a given application (in the range of flow rates of 5,000 to 100,000 scfm and inlet VOC concentrations of 0.1 to 1.0 lb VOC/1000 scf) based on costs without evaluating the site-specific aspects of the many tradeoffs that exist. Selection of the better adsorption system should therefore be based on an integrated evaluation of all the benefits and drawbacks for each type of system.

Although the PURASIV HR system has been promoted for controlling emissions of water-soluble and/or reactive solvents (such as ketones, aldehydes, esters, and organic acids) it is not uniquely qualified for these applications. Water will be present in the solvents desorbed from PURASIV HR systems as well as from fixed-bed systems. Also, precautions to minimize conditions that could lead to bed fires must be taken in designing and operating either type of adsorption system. Processing conditions which eliminate/minimize the possibility of bed fires are inherent in the process design for the PURASIV HR system. The basic design of a fixed-bed system must be modified to provide these conditions.

This report has been prepared by IT Enviroscience in fulfillment of Contract No. 68-03-2568. It covers the period from March 1980 to June 1981.

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I. INTRODUCTION

One drawback of the steam-regenerated fixed-bed adsorption technology that has often been applied for solvent recovery/emission control is the inherent contact of water with solvents during the regeneration step. When suitable recovered solvents cannot be produced by decanting them from the condensed steam, additional costs are generated by additional processing steps, such as distillation.

A new approach to vapor-phase adsorption using a fluidized-bed adsorber was developed in Japan. Since it allows the use of nitrogen to regenerate the carbon, the need for additional steps to separate the water-miscible solvents from the water may be reduced. This technology has been licensed by Union Carbide and is being marketed in the United States under the name PURASIV® HR Vapor Recovery System. The PURASIV HR process uses a new type of beaded activated carbon that was specifically developed to resist attrition, a major disadvantage of previously developed continuous-flow adsorption processes. The advantages of this fluidized-bed adsorption system are reported to be the ability to desorb the organic from the carbon with reduced water contamination, the ability to use inert gases during regeneration, and the low energy consumption.

The goal of this task order is to perform an engineering evaluation of the PURASIV HR technology. This evaluation was accomplished by first reviewing the data available from commercial installations in the United States to identify a site suitable for field sampling. Field sampling tests were then conducted to assess the performance and economics of the PURASIV HR system. The tests included the determination of inlet and effluent concentrations, mass emission rates, and the quality of the recovered solvent. Reliability, cost effectiveness, and energy requirements were also assessed.

The information gathered in this evaluation of the performance of the PURASIV HR system is presented in three sections. The first section discusses the

general principles of carbon adsorption and fluidized-bed adsorption, and the properties of the PURASIV HR carbon and the PURASIV HR process. The second section describes the selection of the test site and the results from the on-site evaluation. The second section also includes data received from another operating PURASIV HR system. The third section compares fixed-bed adsorption systems to fluidized-bed adsorption systems. The comparison includes a discussion of pretreatment requirements, carbon usage, bed designs, regeneration methods, additional equipment needs, safety considerations, and capital and operating costs.

Throughout this report gas-phase concentrations that are expressed as ppm refer to mole percentages.

II. CONCLUSIONS

A. This engineering evaluation of Union Carbide's PURASIV HR adsorption technology has shown that it can be viable for solvent recovery/emission control applications and can compete with fixed-bed systems. However, neither type of adsorption system (fixed-bed or PURASIV HR) can be excluded from a given application based on costs without evaluating the specific aspects of the many tradeoffs that exist. For example, it is true that PURASIV HR systems will require less energy (for desorption) and less electrical power (to move the solvent-laden air through the adsorption system) than fixed-bed systems. But these cost savings are sometimes offset by higher capital costs and higher carbon replacement costs due to shorter carbon lifetime and/or higher carbon prices.

Similarly, the PURASIV HR system has been promoted for controlling emissions of water soluble and/or reactive solvents (such as ketones, aldehydes, esters, and organic acids) because the regenerating fluid is not steam and conditions inside the equipment minimize the possibility of a bed fire. However, fixed-bed systems can also be considered for these applications because the solvent from the PURASIV HR unit may still contain enough water (5 to 10% when the regeneration conditions have been properly adjusted) to require further treatment. Also fixed-bed systems can be and have been designed and operated so that the possibility of a bed fire is greatly reduced. The magnitude of precautions taken in designing operating either type of adsorption system often depends on the corporate safety policies of the companies considering installation of adsorption systems.

B. Installed capital costs for basic PURASIV HR systems are ~40% higher than the capital costs for comparable fixed-bed systems because the PURASIV HR systems are different. However, over a large portion of the range of flow rate and inlet VOC concentration considered, the difference between annual costs for the two types of adsorption systems are within the error bounds of the calculations. Significant differences between the annual costs existed only for the cases at

the lowest flow rate (where costs for PURASIV HR systems were higher) and at inlet VOC concentrations above 0.5 lb VOC/1000 scf (~2250 ppm) when 1.0 lb steam/lb carbon was needed for regeneration of fixed-bed systems (where costs for fixed-bed systems were higher).

C. Both types of adsorption systems can be cost effective when the inlet concentration is greater than 0.1 lb VOC/1000 scf (~450 ppm) and the flow rate is above 5,000 scfm. For these cases, there are enough adsorbed volatile organic compounds (VOC) over which to spread the operating costs so that the cost/lb VOC is near or below the range of replacement costs for typical solvents ($0.20 to 0.40/lb VOC).

D. Mechanical problems such as erosion of the equipment and excessive carbon losses due to attrition have not been experienced with the PURASIV HR systems. Such problems were overcome by replacing the granular activated carbon that was used in other continuous-flow adsorption systems with the spherical, beaded activated carbon developed in Japan.

E. The beaded activated carbon frequently has a shorter lifetime than granular activated carbon. The shorter lifetime may be due to the fact that there is usually less carbon in a PURASIV HR system and circulation of the carbon exposes all of it to the materials that are irreversibly adsorbed. These two factors may mean that the beaded carbon can become poisoned faster than granular carbon in fixed-bed systems. The impact of shorter lifetime on operating costs was reduced at Polaroid by thermally regenerating the carbon.

F. Pretreatment considerations are generally the same for fixed-bed and PURASIV HR systems because the same principles of adsorption influence the operation of both systems. However, the PURASIV HR system is more susceptible to conditions that cause the carbon to agglomerate (sticky solids or liquids) because the agglomerated carbon particles quickly interfere with the circulation of the carbon. The design of early PURASIV HR systems was affected by "shot" upsets of high VOC concentrations because locally high VOC concentrations lead to conden-

sation in the desorption section. Union Carbide now reports that the design has been changed to correct this problem.

G. The outlet concentration from a PURASIV HR system is influenced most by the conditions of the carbon after regeneration. Optimization of the regeneration process is possible to some extent by independently adjusting the carbon flow rate, the nitrogen flow rate, and/or the desorption temperature. From this standpoint, there is more flexibility available for designing and operating a PURASIV HR system than for a fixed-bed system.

III. RECOMMENDATIONS

A. PURASIV HR systems should be considered as an alternate to fixed-bed adsorption systems for solvent recovery/VOC emission control applications. Selection of the type of adsorption system should not be based on one or two features of either system. Selection should be based on an integrated evaluation of all the benefits and drawbacks of each type of adsorption system.

B. Neither type of adsorption system should be categorically excluded from applications that include water-soluble or reactive solvents because neither type of system is uniquely qualified for these applications. Water will be present in the desorbed solvent from either type of system, but it is likely to be higher with fixed-bed systems. Also, precautions must be taken in designing and operating either type of adsorption system to minimize the conditions that can lead to bed fires. Processing conditions which eliminate/minimize the possibility of bed fires are inherent in the process design for the PURASIV HR system. The basic design of a fixed-bed system must be modified to provide these conditions.

C. The presence of liquids in contact with the carbon in PURASIV HR systems should be avoided because the carbon distribution and circulation will be affected drastically.

D. When the carbon must be replaced frequently, methods to prevent the loss of adsorption capacity should be evaluated. These methods include pretreatment to remove from the inlet stream the materials that cause loss of capacity and/or periodic treatment of the carbon via solvent regeneration or thermal reactivation.

E. On-line sampling equipment should be checked frequently. Carbon fines should be specifically excluded from the sampling equipment to ensure that the analyzer is receiving a representative sample from the process.

IV. DESCRIPTION OF FLUIDIZED-BED ADSORPTION SYSTEMS

A. ACTIVATED CARBON ADSORPTION

Vapor-phase carbon adsorption is a versatile and valuable air pollution control technology because it is usually the only nondestructive technique that can effectively and economically remove VOC from atmospheric emissions when the exhaust concentrations are below 5,000 to 10,000 ppm.

Carbon adsorption involves three distinct operations: adsorption, regeneration, and preparation for adsorption service again. This sequence of operations first removes the VOC from the dilute gas stream and then concentrates the organics in liquid form (via desorption from the carbon and then condensation) to facilitate reuse or disposal of the VOC. Attention is called to the fact that carbon adsorption by itself does not treat the emission, it only provides a way to concentrate the organics present so that they can be handled by conventional chemical engineering unit operations.

The most widely used adsorption system design has been multiple fixed beds of carbon with each bed going through the sequence of batch operations described above. Such a system is designed so that at least one bed is always adsorbing organics from the process emission to provide for continuous emission control. Spent adsorbers are removed from adsorption service, regenerated usually by direct contact with steam, and then cooled to prepare them for adsorption service again. When adsorbers are not cooled, removal efficiencies are low because hot, wet carbon is not an effective adsorbent.

Selection of the optimum regenerating technique often involves a compromise. Direct steaming of the carbon bed is the most widely used regeneration technique because it is cheap and simple. Steam serves two purposes. It supplies the energy required to heat the carbon and the vessel as well as supply the heat of desorption. Additional steam is required to promote mass transfer by maintaining a concentration gradient between the carbon and the bulk fluid. In fact, the amount of steam required for mass transfer purposes is usually more

than the steam required to satisfy the desorption energy balance. Steam is very effective in raising the bed temperature quickly because it is a more concentrated source of heat than hot gas. It is also a readily available, condensable fluid from which many organics can be easily separated and recovered.

Steam is not always the optimum choice because the advantages mentioned above are sometimes outweighed by other factors. The most prevalent alternate to steam is a hot gas that is recirculated from the heater to the adsorber, to a condenser to separate the desorbed organics, and then back to the heater. The noncondensables from the condenser must be recirculated to prevent the loss of inert gases (when they are used) and to prevent the emission of the VOCs present (the concentration in the condenser outlet is usually at least an order of magnitude higher than the inlet to the adsorber).

Desorption with a hot gas is sometimes augmented by simultaneously applying a vacuum. This approach has been used most often when additional equipment is required to separate water-soluble organics from steam condensate. It has been used when expensive materials of construction are otherwise required for the adsorber when acidic by-products are produced by hydrolysis of organics (such as chlorinated hydrocarbons).

There are many factors that affect the performance of a fixed-bed carbon adsorption unit and that should be considered when designing a system. For further information on the fixed-bed adsorption system please refer to the literature in this area. (1-6)

B. FLUIDIZED-BED ADSORPTION PROCESSES

Several attempts have been made in the last 35 years to develop moving-bed adsorption systems in order to avoid some problems associated with fixed-bed adsorbers and to capitalize on some potential advantages of a continuous process compared to a batch process. A frequent design approach has been to move the carbon continuously from a fluidized-bed adsorption section to a moving dense-bed desorption section and then to a cooling section before returning the carbon

to the adsorption section. Since a fluidized bed is homogeneous, the adsorption section usually contains multiple trays to gain the efficiency of stagewise operation. Mass-transfer efficiency is further promoted in the adsorption section by the countercurrent movement of the carbon and the waste gas. Countercurrent movement of the carbon and the desorbing fluid also promotes improved mass-transfer efficiency in the desorption section. (6,7)

This design approach offers some potential advantages over fixed-bed adsorbers. Smaller cross-sectional areas for the adsorption section are possible because the lower pressure-drop characteristics of fluidized beds allow the use of linear velocities up to 240 ft/min. Also, the possibility of bed fires in the adsorption section due to hot spots is greatly reduced because there is good transfer of heat throughout the fluidized bed. There is also very little potential for creating bed fires in the desorption section when a heated inert gas is used as the regenerating agent. Safety shutdown instrumentation further reduces the potential of bed fires in the desorption section. Finally when a heated inert gas is used, energy consumed during desorption can be decreased, because a form of energy, namely steam, is not also used to sweep the desorbed organics away from the carbon.

In spite of the above advantages, there were few instances where moving-bed adsorbers have successfully competed with fixed-bed adsorbers because of the following factors. The mechanical complexity of the moving-bed systems has usually made them more expensive than fixed-bed systems. Moving-bed systems have internal heat exchangers, perforated trays for the fluidized-bed section, and sealing sections to isolate the adsorption and desorption sections from each other. In contrast, fixed-bed adsorbers are essentially tanks with carbon supports. In addition, use of commercially available granular activated carbon in moving-bed processes led to increased operating costs because of erosion of the equipment and because of higher carbon losses due to attrition. Filters were often required to reduce emissions of particulates. (6,7)

C. PURASIV HR CARBON

A new form of activated carbon permitted the commercialization of a proprietary fluidized-bed adsorption process in Japan by Kureha Chemical Co., Ltd. That process has been licensed by Union Carbide Corporation for sale in the U.S. under the PURASIV HR trademark. Table 1 shows some general properties of the PURASIV HR carbon. The beaded activated carbon is produced from molten petroleum pitch that yields an activated carbon with equilibrium loadings comparable to activated carbon from other sources. The main features of the PURASIV HR carbon that make it suitable for use in a fluidized-bed adsorber are its spherical shape, narrow particle size distribution, and high resistance to attrition. The spherical shape facilitates transfer of the carbon, particularly in narrow passages such as the heat exchanger tubes in the desorption section. The narrow size distribution prevents flow distribution problems caused by classification of the carbon particles within the equipment. Resistance to attrition will minimize the carbon losses that were experienced with conventional granular activated carbons. (7)

D. PURASIV HR ADSORPTION SYSTEM

1. System Description

Figure 1 presents the flow diagram for the PURASIV HR installation at Polaroid's Waltham, Massachusetts, plant. This diagram is typical of PURASIV HR technology which usually consists of one main vessel that houses a multistage, countercurrent fluidized-bed adsorption section, a moving-bed desorption section, a cool-down section, and a carbon recycle system. The carbon flows from the top of the column to the bottom. In the desorption section various regenerating agents such as nitrogen, air, or steam can be used and heating can be accomplished directly or indirectly. The method of regeneration will depend on the particular application. The method that has the most advantages for the greatest number of organics uses nitrogen as the regenerating fluid with indirect steam heating. This method prevents mixing of steam and organic material and reduces the need for additional separation operations which would be necessary for water-miscible solvents. Nitrogen is preferred over air because of the danger of bed fires due to reaction of oxygen with some organic

Table 1. Properties of PURASIV HR Carbon[a]

Shape	Sphere
Particle size	0.59-0.84 mm
Mean particle size	0.7 mm
Bulk density	0.58-0.61 g/cc
Surface area	800-1200 m^2/g
Adsorption activity	
Benzene	300-400 mg/g
Carbon tetrachloride	600-650 mg/g

[a]See reference 7.

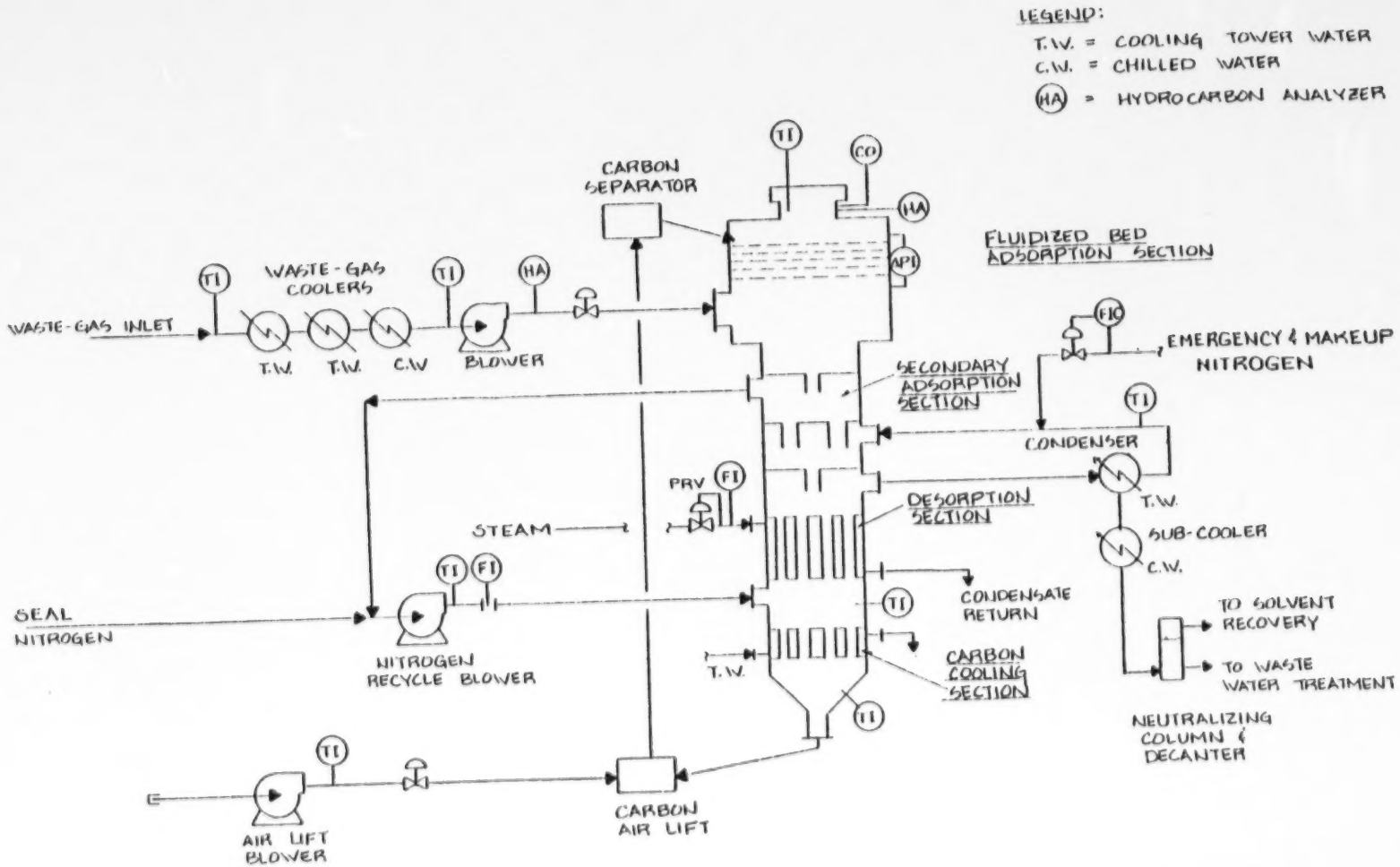


Figure 1. PURASIV HR System at Polaroid, Waltham, Mass.

materials in the presence of carbon as a catalyst. The more detailed description of the PURASIV HR process to follow will describe only the nitrogen regeneration system. However, it should be noted that other options are available.

The adsorption section consists of multistage fluidized beds. The number of stages required depends on the application for which the unit is designed. There are usually 5 to 8 stages required for solvent recovery and 2 to 4 stages required for odor control. The carbon enters the top of the adsorption section via an air lift and moves across each fluidized-bed tray over a weir to the next tray. Uniform distribution of the waste gas and the carbon is critical to the operation of the adsorption section because it ensures proper fluidization of the carbon and provides uniform contact between the carbon and the waste gas stream.

When the carbon leaves the last adsorption stage, it drops into a sealing zone. The carbon flows by gravity from this sealing zone through the desorption section all the way to the bottom of the cooling section in a moving, dense bed. Nitrogen flows countercurrently to the carbon to maintain a concentration gradient. The sealing zone excludes organic-laden air from the desorption section to prevent mixing oxygen and organics in the presence of carbon at high temperatures. The seal is established because the pressure drop across the dense carbon pile flowing through the tubes that extend from the carbon seal pot into the desorption section is greater than the pressure drop across the adsorption section. Added protection against introducing oxygen into the regeneration zone is provided by maintaining enough nitrogen pressure in the regeneration section (measured in inches of H_2O) to produce a small flow of nitrogen from the regeneration section into the adsorption section.

Regeneration is accomplished in two steps. First, the carbon passes through a secondary adsorber where the carbon removes uncondensed VOC from the nitrogen outlet of the condenser so that the recirculated nitrogen will be suitable as a regenerating fluid. The adsorption capacity and driving force to do this are available because the VOC concentration in the condenser outlet is normally at

least 10 times greater than the waste-gas inlet to the adsorption section. This design approach is usually more efficient than directing the outlet of the condenser to the bottom of desorber section.

The carbon leaving the secondary adsorber passes through another sealing zone and into the tubes of a shell-and-tube heat exchanger where the carbon is heated to the desorption temperature by heating media such as steam or Dowtherm in the shell. The desorbed VOC is swept from the desorption section upward through the tubes to the condenser where the bulk of the VOC is separated from the nitrogen. This condenser often uses chilled water to minimize the VOC concentration in the outlet.

The nitrogen loop is completed by recirculating the nitrogen from the vapor outlet of the secondary adsorption zone through a blower to the bottom of the desorption zone. Make-up nitrogen is added to replace the nitrogen that is lost through the seal areas. The regenerated carbon passes downward through another heat exchanger to cool the carbon in preparation for adsorption service again. After the carbon is cooled, it is blown back to the top of the fluidized-bed section via an airlift. If this cooling section were omitted, the carbon would be cooled on the top trays of the fluidized-bed section; however, the effluent quality would suffer because hot carbon is not an effective adsorbent.

2. Design Considerations

As with fixed-bed systems, there is flexibility in designing a PURASIV HR system so that it can be tailored to each application. Much of this flexibility is related to the design of the desorption section because it is the section that is influenced most by the characteristics of each application. In contrast, the design of the adsorption section is more a function of the fluidized-bed adsorption process itself than of the specific application. For example, the adsorption section is usually designed and operated to give a superficial gas velocity of 200 ft/min ±10% to provide enough velocity to fluidize the carbon without creating an excessive pressure drop across the adsorber. Similarly, the number and depth of the adsorption stages can be variables. However, experience has

shown that a bed depth of 1 to 2 inches gives good performance and that 6 to 8 stages are adequate for solvent recovery applications, and 2 to 4 stages are suitable for odor control applications. The pressure drop per stage is 0.4 to 0.9 in. H_2O and depends on the particle density and weir height. The total pressure drop across 6 stages for normal solvent recovery applications would be 2.4 to 5.4 in. H_2O.

An important design and installation consideration is the leveling of the trays in the fluidized-bed section. This is important because when the trays are not level, poor adsorption performance will result because the bed depth will not be uniform. Union Carbide reported that the unlevel trays in one installation were caused by a tray design that is not typical of other systems Union Carbide has since designed. (8)

Experience has also shown that there is an upper limit for both inlet flow rate and inlet VOC concentration that can be accepted by one adsorption section. The upper limit of 40,000 cfm for flow rate is the product of the maximum practical diameter of ~16 ft and the perferred design velocity of 200 ft/min. The limitation on the diameter is imposed by considerations for equipment shipment. For applications with flow rates above 40,000 cfm, multiple adsorption sections with one or more desorption sections should be used.

The inlet VOC concentration is limited by two factors. Compliance with insurance codes often requires maintaining the VOC concentration below 25% of the lower explosion limit (LEL). Since the LEL for many common organic chemicals is in the range of 1 to 3%, this criterion would limit the inlet VOC concentration to 2500 to 7500 ppm. When this criterion does not apply, the inlet VOC concentration must be limited to ~10,000 to 20,000 ppm for many materials to prevent excessive temperature increases in the adsorption section due to heat of adsorption. When the adsorption temperature increases, adsorption loading capacity usually decreases and the outlet VOC concentration usually increases. This fact is true for both fixed-bed and fluidized-bed systems. Inlet air coolers can be used for both types of systems to mitigate the effect of increased bed

temperatures due to heat of adsorption. Both types of systems can also incorporate heat exchange surfaces in the design of the adsorbers.

Much of the flexibility in tailoring a PURASIV HR system to fit a given application is associated with the design of the desorption section. This fact requires specification of the following:

(1) Regenerating agent (nitrogen, air, carbon dioxide or steam)
(2) Heating method (indirect or direct)
(3) Flow rate of carbon
(4) Flow rate of regenerating agent
(5) Desorption temperature
(6) Internal heat transfer surfaces (when required)
(7) Condenser for recovery of desorbed organics

The flexibility in design and operation of the desorption section is a result of the ability to independently select the carbon flow rate, the flow rate of the regenerating agent, and the desorption temperature.

V. EVALUATION OF OPERATING PURASIV HR ADSORPTION SYSTEMS

A. SELECTION OF SAMPLING SITE

The objective of this task was to assess the performance of the PURASIV HR system by first conducting field tests of a full-scale system. The first phase therefore was to select a site where meaningful field tests could be made.

As of April 1, 1980, there were four full-scale PURASIV HR systems installed in the United States. Table 2 shows the location, size, and status of each system. The selection of Polaroid as the site for sampling was influenced by a combination of technical and practical factors. It was a desirable site from a technical viewpoint because the unit was in service (i.e., startup activities were complete) and Polaroid agreed to provide the resources that would facilitate data collection. One practical factor that made the selection straightforward was that the Ford and Donnelley units were not operating at the time. Arrangements were also made to receive the results of experimental tests that were in progress at the time on the General Motors system.

Since the time of this evaluation, additional PURASIV HR systems have been designed and installed. Union Carbide should be consulted for an up-to-date list of applications.

B. PURASIV HR SYSTEM AT POLAROID

1. Description of the System

The purpose of the PURASIV HR system at Polaroid is to collect and recover the mixed ketones emitted from a film coating operation. The ketones will be identified only as ketone A and ketone B throughout this report because their identities are proprietary.

The PURASIV HR system flow diagram at Polaroid was shown in Figure 1. The solvent-laden air first went through a series of coolers and then a blower to the adsorption section. The adsorption section had five fluidized-bed trays and

Table 2. Commercial PURASIV HR Systems
Installed in the United States

Company	Application	Solvent	Flow Rate (cfm)	Inlet Conc. (ppm)	Effluent Conc. (ppm)	Status April, 1980
Ford Motor Co. Michigan	Automotive coat spray	Mixture	6,000	500	<50	Shut down
R. R. Donelley and Sons Tennessee	Gravure printing	Mixture	78,000	1500	<50	Shut down
Polaroid Corp. Massachusetts	Photographic film coating	Mixed ketones	5,000	2000	<60	Operating
General Motors California	Automotive coat spray	Mixture	20,000	250	<20	Experimental test runs

the carbon flowed counter-current to the air stream. The regeneration of the carbon and recovery of the solvent were achieved by using nitrogen that was heated indirectly by steam. The solvent was condensed from the nitrogen stream and subcooled before it was processed in a neutralization column to remove acidic by-products. The recovered solvent was upgraded and mixed with fresh solvent. The water content of the recovered solvent was low, so little distillation had to be done to upgrade the solvent.

2. Results from Startup Testing by Union Carbide Corporation and Polaroid Corporation.

Data generated during the startup activities to optimize the carbon flow rate and the regeneration temperature are shown in Table 3. These data show the impact of carbon flow rate and regeneration temperature on the outlet concentration, VOC removal efficiency, and water content of the recovered solvent. Note that the recovered solvent contained water even though steam was not used for regeneration. Water is present because it is also desorbed from the carbon by the hot nitrogen.

The amount of water in the recovered solvent decreased when the carbon flow rate was reduced, primarily because the higher organic loading on the carbon reduced the amount of adsorption sites that were available to adsorb water. The third set of data, which is said to be typical of normal operation of the PURASIV HR process, shows that the process can be adjusted to reduce the amount of water present in the recovered solvent without severely altering the organic removal efficiency.

In addition to the performance data presented in Table 3, it was reported that few operational problems with transfer of the carbon were experienced during startup. The beaded activated carbon flowed well between sections as long as no liquids were present. In addition, inspection of internals of the equipment showed no evidence of erosion of the equipment.

3. First On-Site Performance Evaluation

The goals of the field tests were to verify operating conditions and utilities

Table 3. Operating Results of Start-up Testing by Union Carbide and Polaroid

Total Hydrocarbon Inlet Concentration (ppm)	Total Hydrocarbon Effluent Concentration (ppm)	Removal Efficiency (%)	Carbon Flow Rate (lb/hr)	Regeneration Temperature (°F)	H_2O in Solvent Recovered (percent)
1500	0-1	99.9	1800	330	40-50
1900	1-2	99.9	1750	275	15-25
2000	10	99.5	1150	260	5-8

consumption and to measure the inlet and outlet concentrations of specific components.

The operating conditions of the PURASIV HR system during the first field tests are indicated on the flow sheet in Figure 2. The conditions shown are the average of the conditions recorded during the three-day sampling period. The variations in the measurements were not significant. The flow rate of the inlet stream to the adsorber was measured at 4800 scfm (1 atm, 68°F). The flow was determined by pitot tube measurements as described by EPA Method 2 -- Determination of Stack Gas Velocity and Volumetric Flow Rate. The flow rate at three different times was 4800 scfm ± 10%.

The steam flow rate measurement was verified by collecting the condensate from the desorption exchanger for two 10-min. periods each at flows of 160 lb/hr and 200 lb/hr. The indicated flow rate was within 5% of the actual measured rate.

Although the process instrumentation included two on-line Beckman total hydrocarbon analyzers, gas chromatographic methods were developed to measure indiyidual concentrations of ketones A and B and to provide an independent check of the on-line instruments. The sampling and analytical plan developed in this project is shown in Appendix A, which shows the conditions for the analyses as well as sample chromatograms from the method development.

The analytical equipment was set up as shown in Figure 3 to sample the inlet and outlet streams by injecting them from two continuously purged sample lines. New sample lines were installed to avoid the possibility of contaminating the samples with material that might have collected in the existing sample lines prior to the field tests. Samples of the inlet and outlet streams were pulled through the sample lines continuously by a vacuum pump. The sampling system was checked before and after each sampling period to assure that there were no leaks in the sample lines. This check was made by verifying that a pressure of 18 in. Hg vacuum was maintained in the sampling system when it was isolated. The field analyses were reproducible within 5% based on multiple injections of the same

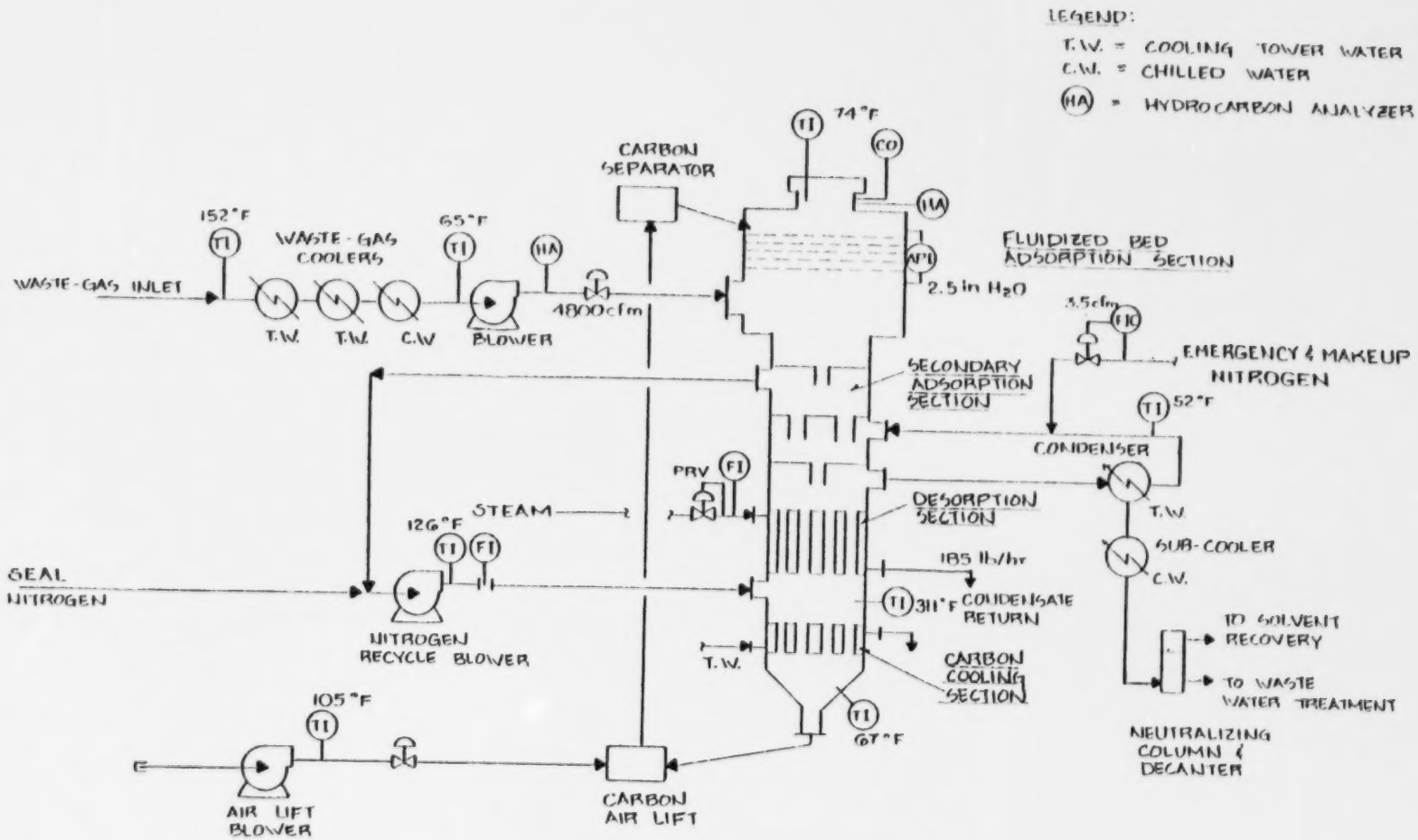
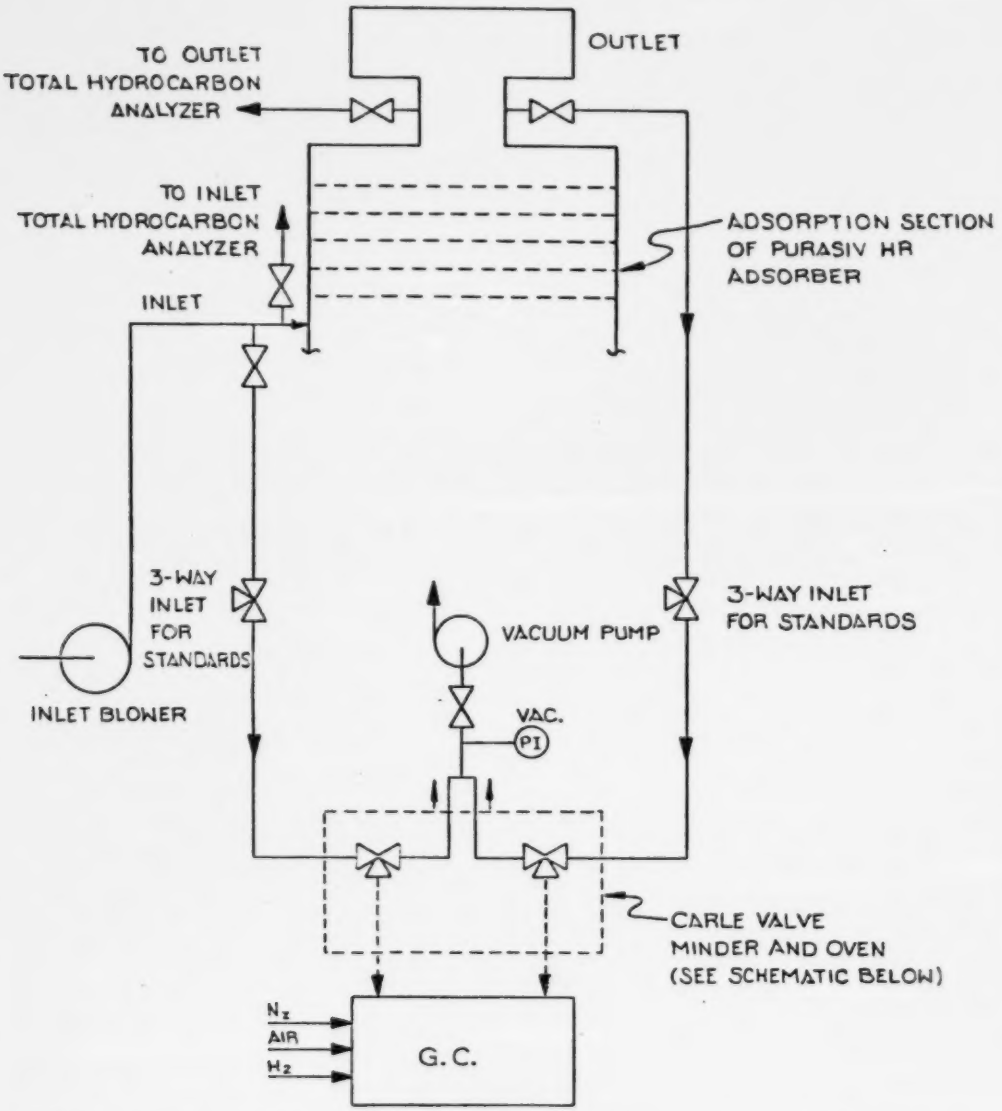


Figure 2. PURASIV HR System at Polaroid, Waltham, Mass.
Conditions During First Field Test - May 29 - June 1, 1980



TYPICAL SCHEMATIC OF CARLE VALVE IN SAMPLING AND ANALYTICAL POSITIONS

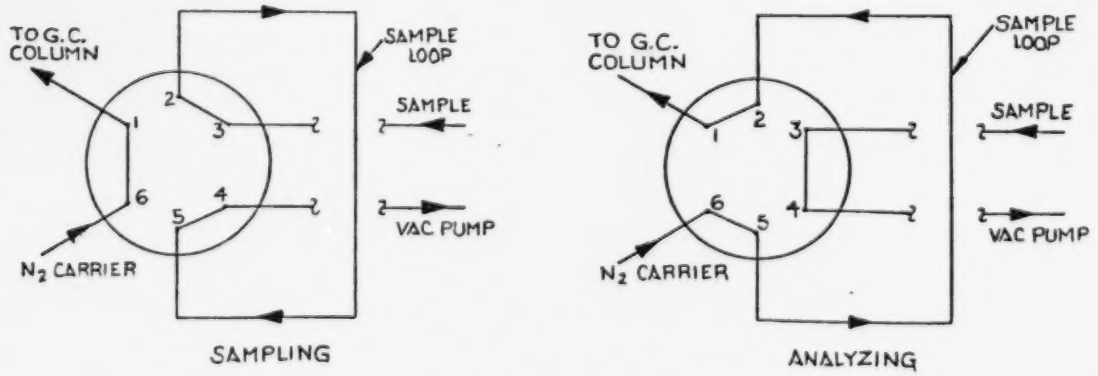


Figure 3. Diagram for Online Sampling and Analyses of Mixed Ketones from Polaroid PURASIV HR System

standard. The field analysis for the independently prepared quality assurance/ quality control audit sample was within 10% of the actual concentration. Sample chromatograms from the field tests are included in Appendix B. No interferences with unknown components were observed.

The analytical results of the first visit to Polaroid are shown in Figure 4. The inlet and outlet concentrations are reported in ppm_v of total mixed ketones. The sampling and analyses of the inlet and outlet concentrations were done during four different time periods from 5/30/80 to 6/1/80. Table 4 compares the average inlet and outlet concentrations for these four time periods with the concentrations of total hydrocarbons (expressed as mixed ketones) obtained from the two existing on-line Beckman hydrocarbon analyzers.

The first field tests were made during a period when the effluent concentration (as measured by the on-line analyzer) was gradually increasing from ~10 ppm ketones one month before the field test to ~160 ppm ketones 10 days after the field tests and up to 250 ppm one month later. (9,10)

Since the desorption section was operating properly, the deterioration in performance was attributed to poisoning of the carbon. This phenomenon is not uncommon for either fixed-bed and fluidized-bed adsorption systems and had been observed on several occasions in PURASIV HR systems in Japan. (11)

Analyses of the carbon by Polaroid and Union Carbide personnel showed that the carbon had been poisoned by "high-boiling cross-linking agents" related to some materials used in the coating process. This determination was made by extracting the carbon with a solvent and analyzing the extract. Discovery of deposits in the ductwork leading to the adsorber was further evidence of the presence of these materials in the waste gas inlet.

When the decision was made by Polaroid to replace the carbon in the PURASIV HR system in July 1980, it provided an opportunity to measure the performance of the system with new carbon in it.

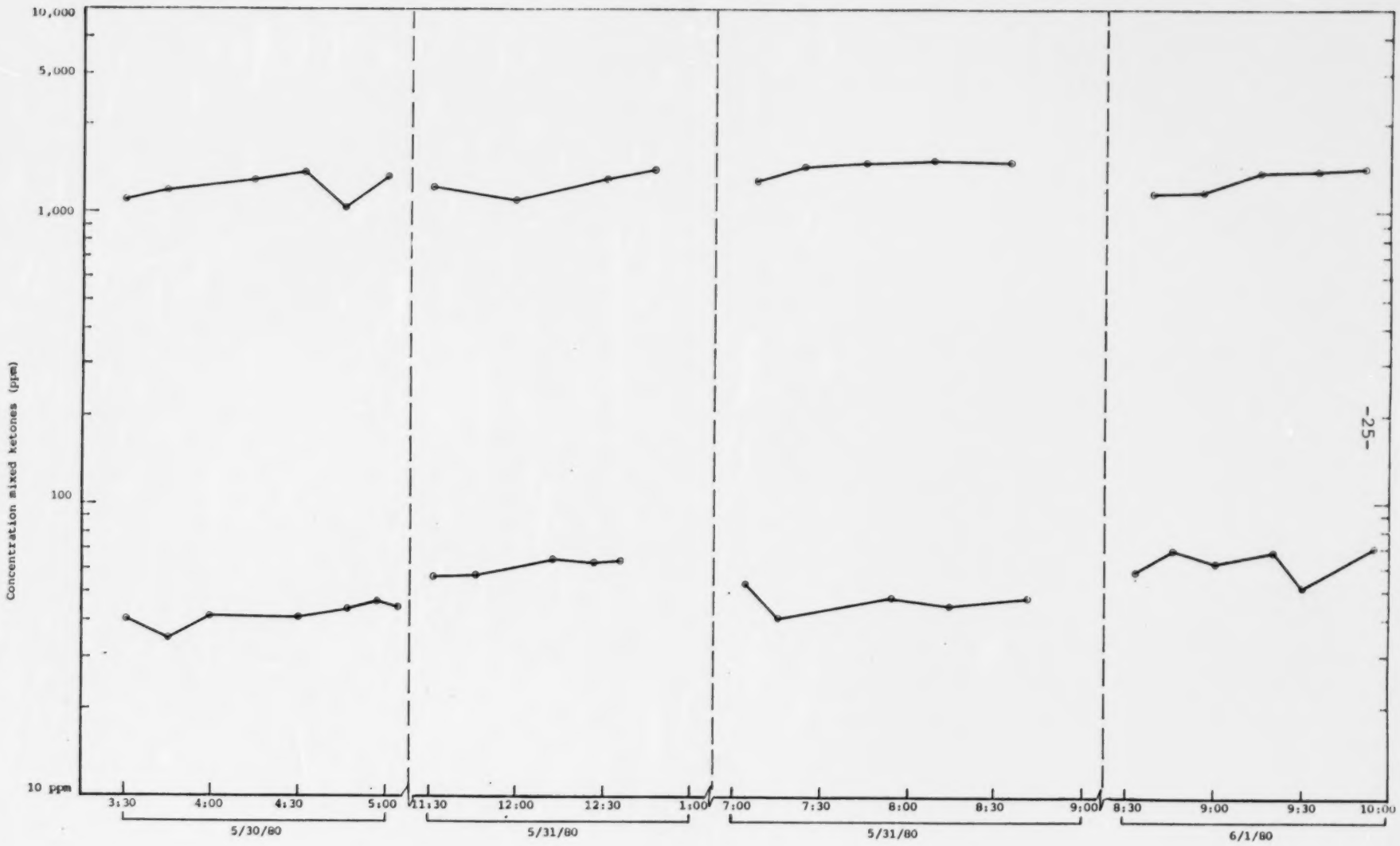


Figure 4. Inlet and Outlet Concentration from Polaroid's PURASIV HR unit - First On-Site Visit

Table 4. Summary of Results of First Field Tests on Polaroid's PURASIV HR System

		GC Analysis			Total Hydrocarbons[b]		
Date	Time	Inlet (ppm)[a]	Outlet (ppm)[a]	Removal Efficiency (%)	Inlet (ppm)	Outlet (ppm)	Removal Efficiency (%)
05/30/80	Afternoon	1211	44	96.4	1480	50	96.6
05/31/80	Morning	1242	64	94.8	1480	64	95.7
05/31/80	Evening	1429	50	96.5	1440	48	96.7
06/01/80	Morning	1325	68	94.9	1520	75	95.1

[a] Mixed ketones as measured by gas chromatography. See Appendix A for methodology.

[b] Online Beckman total hydrocarbon analysis expressed as mixed ketones.

4. Second On-Site Performance Evaluation

The second set of field tests was done during a total of four intervals on 9/11/80 and 9/12/80 using the same procedures as those used during the first field tests. These second field tests were done after the new carbon had been in service for several weeks to avoid characterizing the performance of virgin carbon. The operating conditions for the PURASIV HR system during the second field tests were very similar to the first field tests and are shown in Figure 5.

The inlet and outlet concentrations of mixed ketones as a function of time are shown in Figure 6. Table 5 shows a comparison between the inlet and outlet concentrations of mixed ketones for the four time periods and the average readings of the respective total hydrocarbon analyzers for the same periods.

The results from the second field tests showed that the effluent concentration had decreased (relative to the results from the first field tests) to the range of 10 to 20 ppm mixed ketones. However, it was suspected that one of the analyses for the effluent concentration was in error because the difference between the GC analyses and the total hydrocarbon analyzer was larger than had been experienced in the first field tests. During the first field tests the GC analyses and the total hydrocarbon analyzer agreed within ~10%. During the second tests, the two analytical methods differed by 50 to 60% of the GC analyses. The discrepancy was resolved when a calibration check of both methods showed that the on-line hydrocarbon analyzer had been reading low because the ketones were partially adsorbed by carbon fines in the filter that protected the on-line analyzer from particulates. When the filter was replaced, the agreement between analytical methods was much better, as shown by the data on Table 5 for the afternoon of September 12, 1980.

The collection of carbon fines in the sampling lines and the filter for the analytical instrument could be a symptom of carbon attrition that had been reported for previous attempts to use fluidized-bed adsorbers. However, there are several other pieces of data that indicate that attrition is not a major concern

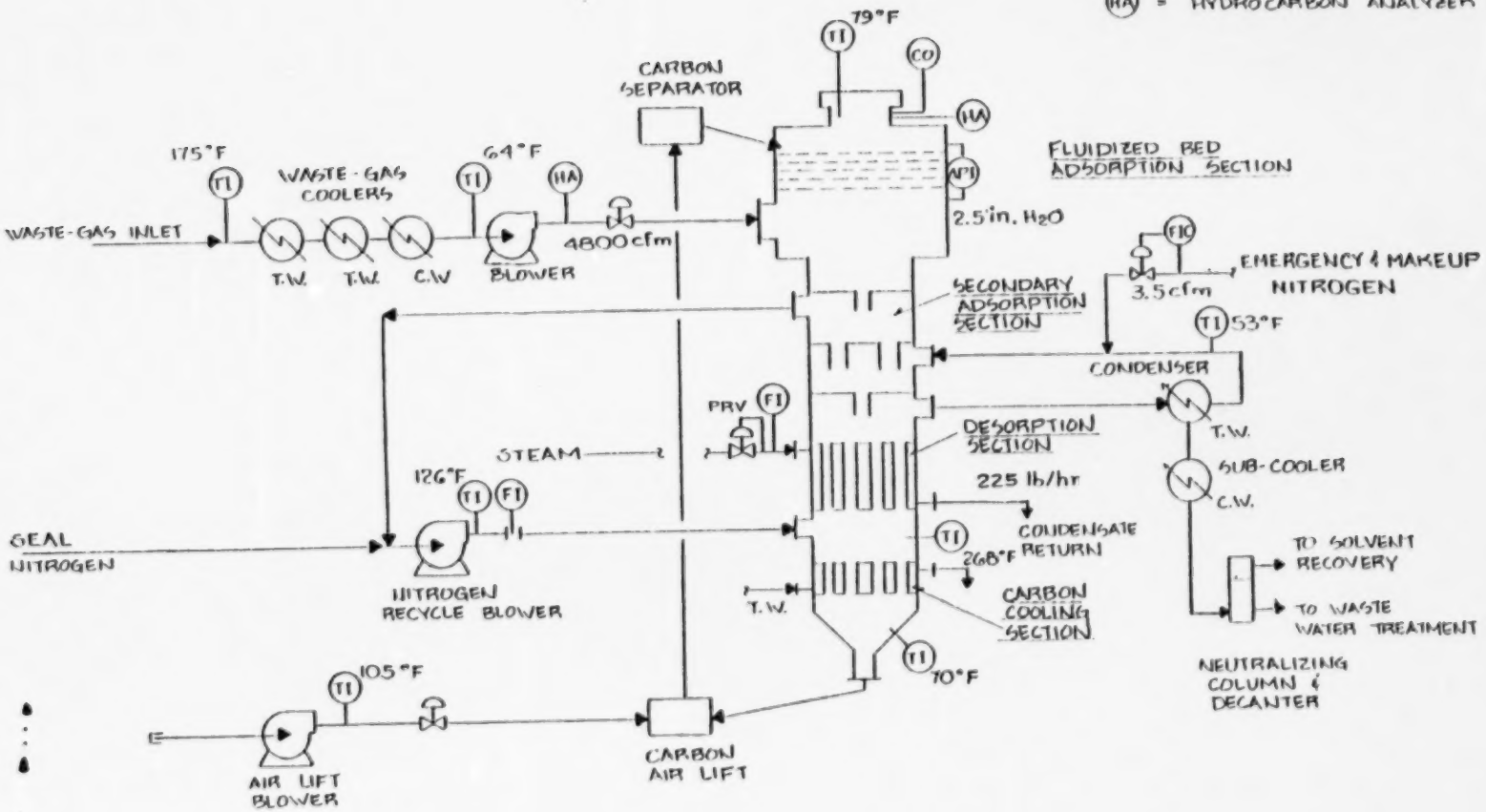


Figure 5. PURASIV HR System at Polaroid, Waltham, Mass.
Conditions During Second Field Test - Sept. 11-12, 1980

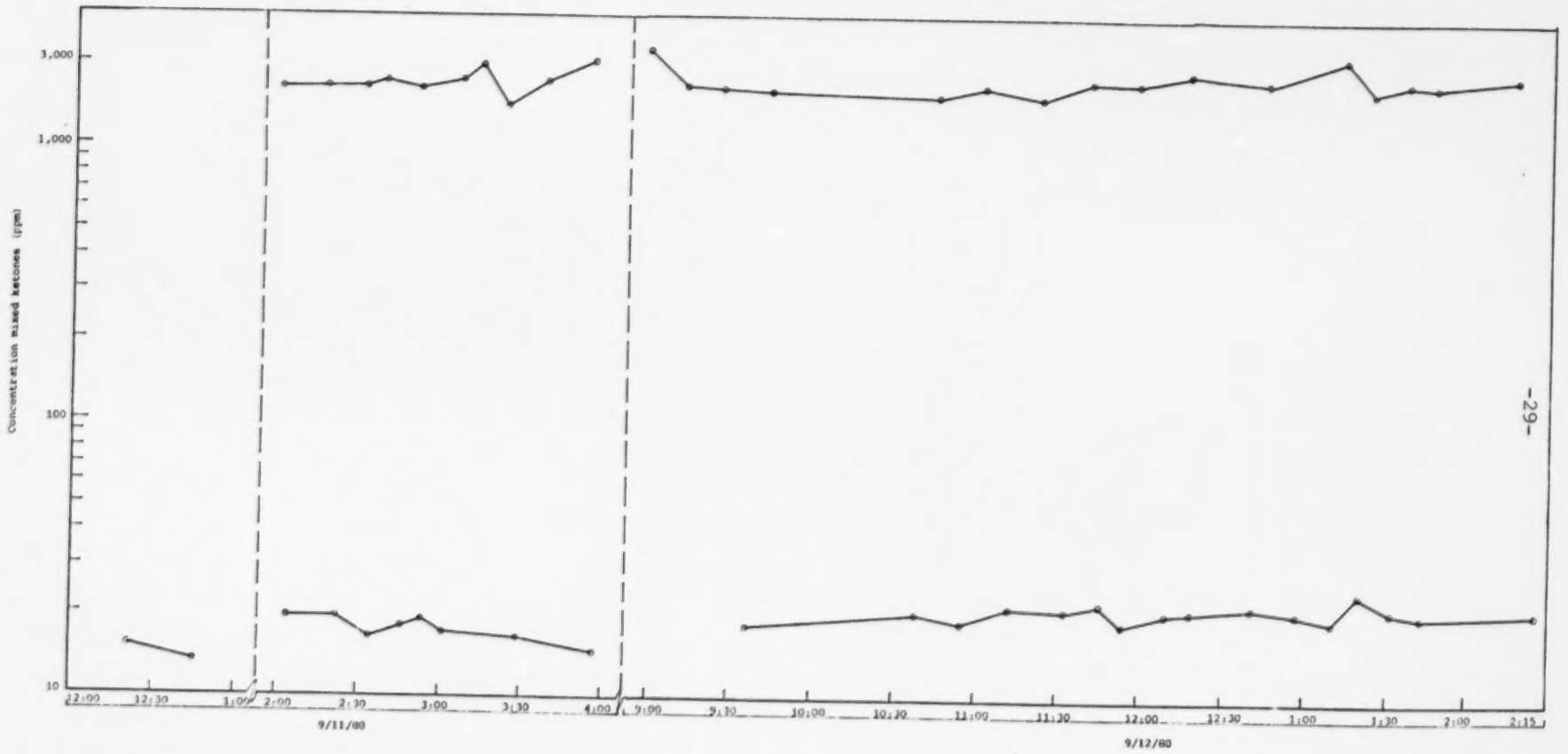


Figure 6. Inlet and Outlet Concentrations from Polaroid's PURASIV HR Unit - Second On-Site Visit

Table 5. Summary of Results of Second Field Tests on Polaroid's PURASIV HR System

		GC Results[a]			Total Hydrocarbons[b]		
Date	Time	Inlet (ppm)	Outlet (ppm)	Removal Efficiency (%)	Inlet (ppm)	Outlet (ppm)	Removal Efficiency (%)
09/11/80	Morning	(no sample)	14	-	1880	7[c]	99.6
09/11/80	Afternoon	1730	18	99.0	1880	7[c]	99.6
09/12/80	Morning	1715	20	98.8	1860	6[c]	99.7
09/12/80	Afternoon	1837	21	98.9	1800	17	99.1

[a]Mixed ketones as measured by gas chromatography. See Appendix A for methodology.

[b]Online Beckman total hydrocarbon analysis expressed as mixed ketones.

[c]Before filter in sample line to Beckman analyzer was replaced.

and that the carbon fines were introduced into the system when the carbon was changed. First, significant carbon attrition would require frequent addition of carbon to the systems. However, Polaroid personnel reported during the initial site visit that <5% of the initial charge (6200 pounds of carbon) had been added during the first 9 months of operation primarily to replace carbon that had been spilled during maintenance activities. The second factor indicating that the carbon fines were introduced during the carbon replacement was the observation of the time when the outlet hydrocarbon analyzer began behaving differently. Before the carbon replacement, the outlet hydrocarbon analyzer read 0 ppm when the system was down, but afterwards the outlet analyzer read 5 to 10 ppm when the system was down. When the filter was replaced, the analyzer read 0 ppm when the system was down as it did before. It is believed that the erroneous reading of 5 to 10 ppm was due to the desorption of ketones from the carbon fines in the sampling system.

5. Summary of Operating Conditions for Polaroid PURASIV HR System

The performance and operating rates of the Polaroid PURASIV HR system summarized in Table 6 are based on the data developed during the on-site tests.

The carbon life of nine months is based on actual experience with the first two batches of beaded carbon. Polaroid reported that the second batch of carbon was replaced when its performance began to deteriorate nine months after the second batch had been charged to the adsorber in July 1980. The yield of thermal regeneration of both batches of carbon was reported by Polaroid to be 60%. It is believed that improved handling procedures for the spherical particles could improve the yield but this has not yet been demonstrated. (10)

The operating data in Table 6 were used to calculate the variable operating costs that are shown in Table 7. Carbon replacement accounts for slightly more than half of the variable operating costs.

Table 6. Performance and Operating Rates of Polaroid's PURASIV HR System

Air flow rate	4800 scfm
Average inlet concentration	1700 ppm_v
Average outlet concentration	19 ppm_v
Hydrocarbon reduction efficiency	98.9%
Amount of hydrocarbon recovered	108 lb/hr
Carbon flow rate	1150 lb/hr
Average carbon loading	0.094 lb organic/lb carbon
Steam usage	
Hourly rate	225 lb/hr
Based on organic material[a]	2.08 lb of steam/lb of organic
Based on carbon rate	0.20 lb of steam/lb of carbon
Electrical usage	15 kWh/hr
Cooling water requirement[b]	14.5 gpm
Carbon life[c]	9 months
Yield of thermal regeneration[c]	60%
Nitrogen usage	3.5 scfm
Quality of recovered solvent	Contains 5% water and is upgraded and reused

[a]This steam usage was measured during the on site testing by ITE. A larger data base collected by Polaroid shows that the ratio of lb steam/lb organic is ∿1.2.

[b]This does not include the cooling requirements of the inlet air stream or the further cooling of the recovered solvent after condensing. Assumed 30°F temperature rise.

[c]Based on experience with first two batches.

Table 7. Projected Operating Costs of Polaroid's PURASIV HR System[a,b]

		Use[c]	Cost
Steam	@ $4.00/1000 lb	225 lb/hr	5,400
Electrical	@ $0.04/kWh	15 kWh/hr	3,600
Chilled cooling water	@ $0.90/1000 gal	14.5 gpm	4,700
Nitrogen	@ $0.40/1000 scf	3.5 scfm	500
Carbon replacement	@ $2.20/lb[d]	8300 lb/yr[e]	18,300
			32,500

[a] Based on 6,000 hr/yr of operation. The actual hours of operation are not known.

[b] Cost factors are given in Table D-4.

[c] From Table 6.

[d] Effective carbon replacement cost based on 60% yield at $1.00/lb C for regenerated carbon and $4.00/lb C for new carbon.

[e] Carbon inventory is 6200 lbs. Usage = $\frac{6200 \text{ lbs}}{9 \text{ mo.}}$ X 12 months/yr.

C. GENERAL MOTORS PURASIV HR SYSTEM

During 1980, the General Motors Assembly Plant in Fremont, California, evaluated several ways including the performance of a PURASIV HR system, to reduce hydrocarbon emissions from the spray painting of cars and trucks. The results of these evaluations were reported to Region IX of the EPA in a report on April 15, 1980, entitled "General Motors Report on Phase I Testing and Phase II Continuous Pursuant to a Delayed Compliance Order Issued on February 25, 1980 by U. S. EPA (Docket No. 9-79-266)." A follow-up report was issued on June 2, 1981. These reports are of interest because they contain independent operating data for another PURASIV HR unit. Therefore, portions of the first report that pertain to carbon adsorption (essentially Phase I) and all of the follow-up report are included in Appendix C for reference.

Comparison of the flow diagram in Appendix C and Figure 1 shows that the PURASIV HR installation at General Motors is very similar to the Polaroid unit except the flow rate is 20,000 cfm and the desorption section is heated by a Dowtherm J liquid system. There are five fluidized-bed trays in the adsorption section and desorption is accomplished by recirculating heated nitrogen through the moving dense bed in the desorption section. The PURASIV HR system was installed on a truck painting line to control the emissions of a solvent mixture containing VM+P naphtha, toluene, methyl ethyl ketone, acetone, methyl isobutyl ketone, butyl acetate, butanol, and cellosolve acetate. (12)

The operating data are summarized in Table 8. The data have been converted from the format reported by General Motors to the format used in Table 6 to facilitate comparison with the data on the Polaroid unit. For example, to account for the fact that the truck line only operated one shift per day, the daily utilities consumption data reported by General Motors were converted to hourly consumption data, based on information supplied by Union Carbide. (8), (13) Also, parameters related to the VOC mass flow rate were based on the molecular weight of propane because the hydrocarbon analyzer response factors for the VOCs present are not known. It is difficult to predict the response factor of this aggregate of solvents because some solvents are likely to be more sensitive than

Table 8. Performance and Operating Rates of General Motors PURASIV System[a]

Emission flow rate	20,000 cfm
Average inlet concentration	94 ppm (as C_3)[b]
Average outlet concentration	10 ppm (as C_3)[b]
Average VOC removal efficiency	89.4%
Average rate of VOC removal	11 lb/hr (as C_3)
Natural gas usage	120 CFH[c]
Desorption energy relative to VOC removed	11,630 Btu/lb VOC[d]
Electricity	29 kWh/hr[e]
Nitrogen	220 cfh[f]
Cooling water	8.6 gpm[g]

[a] From Appendix C.

[b] Propane used for calibration.

[c] Daily consumption divided by 10 operating hr/day. (12)

[d] From natural gas usage and actual rate of VOC removal.

[e] Daily consumption divided by 24 operating hr/day. (13)

[f] Daily consumption divided by 24 operating hrs/day and converted using 93.11 scf/gal. (12)

propane and others are likely to be less sensitive. However, it is not likely that the sum of the individual hydrocarbon concentrations will be less than half of the analyses reported as "C_3". Therefore the actual rate of VOC removal is probably more than the 11 lb/hr calculated (as C_3) because the average molecular weight of the recovered solvent is 96 or more than twice the molecular weight of propane.

The data in Tables 6 and 8 show that, in general, comparable performance was observed for the two PURASIV HR systems. The difference between the observed outlet concentrations is not significant because one is total hydrocarbon as C_3 and the other is the sum of the individual ketones.

The difference between removal efficiencies is not significant because removal efficiency is strongly influenced by the large difference between inlet concentrations. Comparable consumption of nitrogen was observed.

The most significant differences are in the VOC removal rates and the amount of energy required for desorption per pound of organic desorbed. However, it is likely that these differences are not as large as they first appear because of two factors. First, as discussed above, the VOC removal rate for the General Motors unit is probably somewhat higher than the rate calculated as propane. Second, the unit was operated at an organic removal rate substantially less than the design removal rate of 57 lb solvent/hr. (8) (Note again that the conversion from lb solvent/hr to lb propane/hr is uncertain.) Assuming that adequate performance could be achieved by using 120 cfh of natural gas to desorb 57 lb solvent/hr, the calculated ratio of energy consumed to VOC removed would be 2230 Btu/lb VOC, which would be close to the 2.08 lb steam/lb VOC observed during the testing of the Polaroid system.

Another similarity between the General Motors and Polaroid applications is the observed decrease in VOC removal efficiency during the first year of service. General Motors reported a drop in removal efficiency after ~5 months of service. (14) The decrease in adsorption efficiency was not caused by the buildup of

paint solids because (1) testing had shown that the five-stage filter installed with the PURASIV HR system was effective and (2) sticky paint solids entering the adsorber would probably have caused agglomeration of the carbon particles that would have led to conspicuous shutdowns of the system.

Investigation by Union Carbide has indicated that loss in efficiency was due to a "high boiling organic acid which is not present in the raw solvent fumes from the painting operation, but is formed during the continuous regeneration of the carbon." (14) It is not clear if the loss in efficiency was related to the change in service from enamel fumes (truck painting line) to lacquer fumes (car painting line) two months before the loss in efficiency was first noted.

The operating data in Table 8 were used to calculate the variable operating costs shown in Table 9. To provide a comparison with the operating costs projected in Table 7 for the Polaroid unit, a 6000 hr/yr operation (or 24 hr/day, 250 days/yr) was assumed. The data show that slightly more than half the projected operating costs are associated with the relatively short carbon lifetime. Except for the higher costs for electricity, the projected operating costs for General Motors and Polaroid are comparable.

Table 9. Projected Operating Costs of General Motors PURASIV HR System[a,b]

		Consumption[c]	
Natural gas	@ $3/1000 cf	120 cfh	2,160
Electricity	@ $0.04/kWh	29 kWh/hr	6,960
Cooling water	@ $0.10/1000 gal	9 gpm	320
Nitrogen	@ $0.40/1000 ft^3	3.6 scfm	530
Carbon replacement	@ $2.20/lb	2 X 4000 lb/yr	17,600
			27,570

[a] Based on 6,000 hr/yr operation.

[b] Cost factors are given in Table D-4.

[c] Consumption given in Table 8.

[d] Assumes cost and yield of thermal regeneration is comparable to Polaroid's experience. See Tables 6 and 7.

VI. COMPARISON OF FLUIDIZED-BED AND FIXED BED ADSORPTION SYSTEMS

Some of the advantages of a fluidized-bed design over a fixed-bed design were discussed in Section IV-B. These aspects and others are discussed in this section.

Valid comparisons of these two types of adsorption systems require consideration of many technical and economic aspects. For many applications the benefits of some aspects will be offset by the drawbacks of others. Thus selection of the better system should be based on evaluation of all aspects. Sometimes a definitive conclusion will be possible only after a side-by-side comparison has been made for that application. Capital and operating costs and sample calculations are summarized in Appendix D. Many of the individual aspects of the comparison between PURASIV HR and fixed-bed adsorption systems are discussed in the following sections. In some cases the comparisons were illustrated by extracting cost data from the tables in Appendix D.

A. CARBON INVENTORY

The working adsorption capacity is approximately the same for the beaded activated carbon used in the PURASIV HR system and the granular activated carbons used in fixed-bed systems. However, the carbon inventory for the PURASIV HR system will usually be less than for a comparable fixed-bed system because the fixed-bed system must have the capability of having one bed adsorbing VOC while the other one is being regenerated. For example, General Motors installed a fixed-bed adsorption system for the same service as the PURASIV HR unit to provide a direct comparison. The PURASIV HR system contained 4000 pounds of beaded activated carbon compared to a total of 18,400 lb of granular activated carbon in the two fixed-bed adsorbers.

Although the carbon inventory is less for a PURASIV HR system, the purchased cost for the initial charge of carbon is nearly equivalent because the cost of the beaded activated carbon is four times the purchased cost for granular carbon ($4.00/lb vs $1.00/lb).

B. CARBON LIFETIME

Data generated in the U. S. and Japan indicate that the beaded activated carbon used in PURASIV HR systems often has a shorter lifetime than the granular activated carbon used in fixed-bed systems. No PURASIV HR system in the U. S. (General Motors and Polaroid) has been able to maintain effective performance for more than nine months because of the buildup of high boilers. Similar experience has been observed in Japan where the carbon has been replaced and reactivated once a year, especially for printing applications where high boilers are present. (11) It is impossible to know if the observation is simply the result of a small sample size or if all PURASIV HR systems will exhibit this behavior.

The best way to determine whether the beaded activated carbon has a shorter lifetime would be to test fixed-bed and fluidized-bed systems side-by-side in identical service. This was one of the objectives of the evaluations done by General Motors at Fremont, California. However, it is difficult to draw conclusions from these evaluations because the emissions from the car line and the truck line were different, especially considering the presence of butyl carbitol in the solvent used in the car line. (8) In addition, it is not clear if the reported reduction in adsorption capacity of both adsorption systems at General Motors (14) can be correlated with interchanging the paint line exhausts between the two adsorption systems. These data would be more conclusive if the two adsorption systems had been in identical service and exposed to the same high boilers and in the same sequence.

If PURASIV HR systems are shown to have a shorter carbon lifetime the reason could be related to the fact that there is less carbon charged in a given installation (see the discussion in the previous section). PURASIV HR systems would then be rendered ineffective more quickly than comparable fixed-bed systems that contain more carbon.

The shorter carbon lifetime for PURASIV HR systems could also be related to the effect of staging (with respect to exposure to the high boilers) that exists in fixed-bed systems that does not exist in fluidized-bed systems. In fixed-bed

systems, the irreversible adsorption of high boilers occurs at the inlet end of the adsorber so that the bulk of the granular carbon will maintain its ability to achieve low outlet concentration. In fluidized-bed systems, all the beaded carbon is exposed to the high boilers as the carbon is circulated through the adsorber. Since there is less carbon in the fluidized-bed unit, it can become less effective more quickly than a comparable fixed-bed system.

Shorter carbon lifetimes (if they are shown to be characteristic of PURASIV HR systems) and the higher cost of the beaded carbon will offset some of the other economic advantages of the PURASIV HR technology. When the carbon can be thermally regenerated (as it was at Polaroid), the economic impact of shorter lifetimes will be reduced.

C. PRETREATMENT

For many applications of carbon adsorption it can be cost effective to pretreat the inlet to the adsorber. For example, removal of high boilers may be a cost-effective way to extend the useful lifetime of the PURASIV HR carbon. Other forms of pretreatment equipment include coolers (to limit the inlet temperature), condensers (to limit inlet VOC concentrations), filters and mist eliminators (to remove entrained solids and liquids), and heaters (to dehumidify the inlet).

Since the two types of adsorption systems are generally affected by the same factors, differences in pretreatment requirements are frequently a matter of degree. The following sections compare the impact of these pretreatment technologies on fixed-bed and fluidized-bed adsorption systems.

Both adsorption systems will be adversely affected by high temperatures during adsorption because adsorption capacity decreases with increasing temperature. Thus, the inlet temperature to both fixed-bed and fluidized-bed systems should be <35°C. In addition, high adsorption temperatures can also be caused by high inlet VOC concentrations because air flowing through the adsorber is the only way to remove the heat of adsorption that is released unless coolers are used.

The inlet VOC concentrations should therefore be limited to the range of 10,000 to 20,000 ppm. Fixed-bed systems are likely to be less sensitive to very high inlet concentrations because the carbon can contain more residual water after direct steaming that will act as a heat sink to remove the heat of adsorption.

The effects of entrained liquids and solids in the performance of adsorption systems are influenced by the type of adsorption system. For example, dry solids have little effect on a PURASIV HR system because they are usually small enough so that they pass through the adsorption section. In contrast, dry solids will usually remain in fixed-bed systems resulting in poorer adsorption performance because of a higher pressure drop and/or channeling. This deterioration in performance can be gradual or rapid depending on the solids concentration. For low solids concentrations it may be cost effective to accept a shorter carbon lifetime instead of installing a filter to remove the solids from the inlet stream.

Sticky solid particulates such as paint spray mists will coat the carbon particles in either type of adsorption system. However, fluidized-bed systems will be affected more quickly because the agglomerated carbon particles that will be formed will interfere with the circulation and distribution of the carbon. Although fixed-bed systems do not depend on movement of the carbon, sticky solid particles should not be routinely introduced to fixed-bed systems because channeling will make it difficult to maintain good adsorption performance.

Entrained liquids should be removed from the inlet to either type of adsorption system by mist eliminators. When liquid organics are present during adsorption, the removal efficiency usually drops because the adsorption capacity available is exceeded by the increased adsorption capacity required. This phenomenon is aggravated when the additional heat of adsorption is not dissipated to prevent increased adsorption temperatures. In fixed-bed systems the baseline outlet concentrations will increase or premature breakthrough will occur. In PURASIV HR systems the outlet concentration will increase or the process will be shut down because bridging of the carbon particles will have interfered with the circulation of the carbon.

The adverse effects of liquids on PURASIV HR systems also influences pretreatment requirements for applications where temporary "shots" of high VOC concentration are possible because this upset condition can lead to locally high VOC concentrations in the desorption section. If the partial pressure exceeds the vapor pressure and droplets form, the carbon will bridge in the pile above the desorption section. This interruption of carbon flow in the whole system will affect the adsorber operation much longer than the duration of the initial upset. Union Carbide engineers have learned to deal with planned "shots" or extended peaks defined in the duty specification by modifying the design so that the temperature of the carbon in the carbon pile is above the dewpoint of the solvent. The rate of circulation of the nitrogen can be increased to reduce the concentration of the solvent or a carbon preheat section can be included between the secondary adsorber and the desorber heat exchanger. When higher nitrogen circulation rates are used, a larger condenser is usually required.

Fixed-bed systems are more tolerant of a temporary, unexpected "shot" of high inlet concentration because the presence of liquids will not affect the mechanics of the operation. In fact, when steam is used for desorption, liquids are frequently present without any detrimental effects.

The effects of the relative humidity of the adsorber inlet are most pronounced when competitive adsorption between water and the VOC is significant. This is usually true when high removal efficiencies are desired or when the competitive adsorption is not masked by regeneration with steam. For PURASIV HR systems that use nitrogen as the regenerating fluid, the amount of water present in the recovered solvent is influenced most by the availability of adsorption sites as determined by regeneration conditions. Some data on this phenomenon for the Polaroid system were shown in Table 3. For steam-regenerated systems (most of the fixed-bed systems and very few PURASIV HR systems) the relative humidity will influence the effluent concentration. In some applications, the adsorber inlet should be dehumidified by slightly reheating it to give better effluent quality.

D. ADSORBER DESIGN

The fluidized-bed design generates a lower pressure drop across the adsorption section at higher linear velocities than a fixed-bed design does. For example, the optimum range of linear velocities is 50 to 100 ft/min for fixed beds and 200 ft/min (±10%) for fluidized beds. The pressure drop across the adsorber is 5 to 20 in. H_2O for a fixed-bed adsorber and 2.5 to 5 in. H_2O for a fluidized-bed adsorber.

The differences between the optimum linear velocities mean that a fluidized-bed adsorber would have a smaller cross-sectional area for the same flow rate of solvent-laden air. For example, to handle 20,000 cfm, the fluidized-bed adsorber would require 100 ft^2 cross-sectional area compared to 200 to 400 ft^2 for each adsorber in a fixed-bed system. However, this is not a clear-cut advantage for fluidized-bed systems because this advantage is offset by the increased complexity of the fluidized-bed trays, heat exchange sections, sealing zones, and carbon transport system.

Lower pressure drop also means reduced electrical energy consumption. For example, a fluidized-bed system will consume only 25 to 50% as much electricity as a fixed-bed system. Since the absolute value of these savings is directly proportional to the flow rate of the solvent-laden air, this advantage for fluidized-bed systems is more significant at higher flow rates. The data in Table 10 show that the savings in electrical costs are $4610/yr at 5000 cfm and $93,700/yr at 100,000 cfm.

E. REGENERATION

The most significant difference between the two types of adsorption systems is the method of regeneration. Fixed-bed systems generally use steam as the regenerating fluid and fluidized-bed systems normally use recirculating nitrogen that is heated indirectly. The data developed at the Polaroid installation showed that energy consumption for the PURASIV HR system was 2.08 lb steam/lb VOC and 0.2 lb steam/lb carbon. Existing fixed-bed systems installed primarily to recover vaporized solvents normally use ~0.3 lb steam/lb carbon. However,

Table 10. Effect of Flow Rate on Electrical Costs for Fixed-Bed and Fluidized-Bed Adsorption Systems[a]

Flow Rate (cfm)	Type of Adsorption System	ΔP in. H_2O	Annual Electrical Costs[b] ($/yr)	Annual Savings Fluidized Bed vs Fixed Bed ($/yr)
5,000	Fluidized bed	5	1,560	-
5,000	Fixed bed	20	6,200	4,610
100,000	Fluidized bed	5	31,200	-
100,000	Fixed bed	20	124,900	93,700

[a]See Appendix D for operating cost calculations.

[b]At $0.04/kWh.

fixed-bed systems would probably require ~1.0 lb steam/lb carbon to give removal efficiencies comparable to the PURASIV HR system. (4) As discussed in Section IV-B the energy savings are due to a combination of factors. First, the majority of the steam consumed in regeneration of fixed-bed adsorbers is used to promote mass transfer (not supply heat) and passes through the adsorber uncondensed. In the PURASIV HR system, less energy is required because nitrogen, which is not a form of energy, is used to promote mass transfer. Second it is not necessary to alternately heat and cool the equipment shell in PURASIV HR systems as it is in fixed-bed applications.

Since the steam consumption for both types of systems can be expressed in lb steam/lb carbon, the absolute value of the energy savings is directly proportional to the amount of carbon that must be regenerated. Factors influencing the amount of carbon that must be regenerated include the flow rate and VOC concentration of the solvent-laden air, and the carbon loading achieved. Table 11, which compares steam cost data taken from Appendix D, shows that the savings increased dramatically as the amount of solvent to be adsorbed (and hence the amount of carbon to be regenerated) increased. Two different ratios of lb steam/lb carbon for fixed-bed system were used to show the effect of steam consumption on the savings.

It should be noted that the magnitude of the calculated savings shown in Table 11 for high inlet VOC concentration will probably be less because these comparisons did not reduce the carbon consumption to account for higher carbon loadings at higher concentrations (a carbon loading of 0.1 lb VOC/lb carbon was used for all cases). This phenomenon will decrease the magnitude of the calculated savings at the higher inlet concentrations. These comparisons of steam costs also do not account for differences that may exist between carbon loadings of the beaded carbon used in PURASIV HR and carbon loadings of the granular carbon used in fixed-bed systems.

F. RECOVERED ORGANIC RECYCLE SYSTEM

One of the main reasons PURASIV HR systems are considered for vapor-phase applications with water-soluble organics is that they reduce the water in the

Table 11. Steam Costs for PURASIV HR and Fixed-Bed Adsorption Systems

Flow Rate (cfm)	Inlet VOC Conc. (lb VOC/1000 scf)	Steam Cost for PURASIV HR ($/yr)[b]	Steam Cost for Fixed-Bed System Using 1.0 lb Steam/lb C ($/yr)[c]	Steam Cost for Fixed-Bed System Using 0.3 lb Steam/lb C ($/yr)[d]	Savings of PURASIV HR vs Fixed-Bed System Using 1.0 lb steam/lb C ($/yr)	Savings of PURASIV HR vs Fixed-Bed System Using 0.3 lb steam/lb C ($/yr)
5,000	0.1	1,920	9,600	2,900	7,680	980
5,000	0.5	9,600	48,000	14,400	28,800	4,800
5,000	1.0	19,200	96,000	28,800	76,800	9,600
5,000	2.5	48,000	240,000	72,000	192,000	24,000
20,000	0.1	7,860	38,400	11,520	30,540	3,660
20,000	0.5	38,400	192,000	57,600	153,600	19,200
20,000	1.0	76,800	384,000	115,200	307,200	38,400
20,000	2.5	192,000	960,000	288,000	768,000	96,000
100,000	0.1	38,400	192,000	57,600	153,600	19,200
100,000	0.5	192,000	960,000	288,000	768,000	96,000
100,000	1.0	384,000	1,920,000	576,000	1,536,000	192,000
100,000	2.5	960,000	4,800,000	1,440,000	3,840,000	480,000

[a] Calculations shown in appendix D.

[b] Data from Table D-1.

[c] Data from Table D-2.

[d] Data from Table D-3.

desorbed organic because the use of steam as a regenerating agent can be eliminated. The data in Table 3 showed that the concentration of water in the recovered ketones from the Polaroid PURASIV HR unit ranged from 5 to 50% during startup, depending on the regeneration conditions. The water content of the recovered ketones has been typically 5 to 8% since startup. By contrast, the comparable water concentration for a fixed-bed unit would have been 91% water (based on using 1.0 lb steam/lb carbon to establish an outlet concentration of 10 ppm and a working capacity of 0.1 lb VOC/lb carbon). It is important to recognize that the desorbed organics from a PURASIV HR system will still contain some water that may need to be separated.

It is very difficult to calculate on a general basis the impact of reduced water in the recovered organics because the cost of separating the water will depend on the solubilities of organic in the water and water in the organic, the amount of water that can be tolerated in the process, the relative volatilities, the formation of azeotropes with water, and the value of the solvents. It will also depend on the availability of water-solvent separation equipment in the existing process. This evaluation has not been done because it is a very complex one that will often be specific to a given application.

G. SAFETY CONSIDERATIONS

Other factors that must be considered when comparing types of adsorption systems are the safety considerations associated with the adsorption of reactive solvents. Activated carbon or its impurities can catalyze the decomposition of some organics, such as ketones, aldehydes, and possibly organic acids and esters, especially at elevated temperatures in the presence of oxygen. These exothermic decomposition reactions can generate localized hot spots and/or bed fires within an adsorber if the heat is allowed to build up. These hazards will crop up if the flow is low and the inlet concentrations are high, or if an adsorber is left dormant without completely regenerating the carbon.

A fire hazard can also exist during the virgin operating cycle, because little water is present on the carbon to act as a heat sink and because more material is adsorbed during this cycle than during other cycles.

The basic design of the PURASIV HR system helps to minimize the conditions that can lead to bed fires. The recirculating nitrogen essentially prevents the contact of oxygen with the carbon at the elevated temperatures in the desorber. Furthermore, the agitation in the fluidized bed improves heat transfer and helps prevent the generation of hot spots in the adsorption section.

Although PURASIV HR systems have these design features, experience has shown that fixed-bed systems cannot be categorically excluded from these types of applications. For example, the careful selection of activated carbon and operating procedures has enabled General Tire and Rubber Company to recover methyl ethyl ketone from its fabric coating operation for over 15 years without incident. (15) In addition, General Motors reported that no bed fires were experienced during the operation of the fixed-bed adsorption unit that was installed with the PURASIV HR unit at Fremont, California. It is not known if this was due to the fact that the concentration of ketones was <5% for the enamel line and 18% for the lacquer line (8) or to the use of nitrogen "to protect against bed fires on partially adsorbed beds during downtime." (12)

The following procedures (16) are usually recommended to reduce the hazard of fires in fixed-bed adsorbers:

1. The carbon should never be left dormant unless it has been thoroughly regenerated.

2. Design parameters should be set so as to avoid high inlet concentrations and low flow.

3. Instrumentation, including alarms, should be installed to monitor the temperature change across the adsorber bed and the outlet concentrations of CO

and CO_2. The instrumentation should signal the first signs of decomposition, so that any acceleration leading to a bed fire can be forestalled.

4. A deluge system should be provided to water-cool the bed in the event of an excursion.

5. Virgin carbon should be steamed before the first adsorption cycle. Evaporation of residual condensate will remove heat of adsorption.

It is not clear if these procedures are also valid for PURASIV HR applications. Many were used in the design and operation of the Polaroid PURASIV HR system but Union Carbide believes that "the inert atmosphere within the desorber with its associated safety shutdown systems makes the desorber intrinsically safe." (8)

H. ACHIEVABLE OUTLET CONCENTRATION

Neither adsorption system will routinely achieve a lower outlet concentration than the other. Maintenance of good effluent quality for fixed-bed systems requires effective desorption and close control of materials (such as organics, particulates, and water) and/or conditions (such as elevated temperature) that impair adsorption. The heel of organic that is left on the carbon after desorption will influence the equilibrium and dynamics of the next adsorption cycle. The data that were generated for the Polaroid PURASIV HR system demonstrate that these concepts also apply to fluidized-bed systems. The data in Table 3 showed that when the beaded carbon was new, the outlet concentration was influenced by the regeneration conditions (i.e., carbon flow rate and regeneration temperature). Later during the two field tests (Tables 4 and 5) the outlet concentration was influenced most by the gradual buildup of high boilers.

Data on both types of adsorption systems show that outlet concentrations of 10 ppm can be achieved if the carbon is maintained in good condition. Outlet concentrations below 10 ppm are possible with either type of adsorption system but operating costs will probably be higher because of higher pretreatment costs, higher desorption energy costs, and possibly shorter carbon lifetimes.

I. CONDENSER

Although the condenser duty and service are not the same for the two types of adsorption systems, the sizes for the condensers are nearly the same for comparable adsorption service. The condenser for the fixed-bed system must transfer heat at a rate about forty times faster because more energy is used at a higher rate due to batch desorption. However, the heat transfer coefficient for a condenser where essentially all the vapor is condensing will be about 7 to 10 times greater than the heat transfer coefficient for a cooler where only 10 to 15% of the vapors are condensed (150 Btu/ft^2 hr°F for the former and 15 to 20 Btu/ft^2 hr°F for the latter). Since the temperature difference across which most of the heat is transferred will also be greater for the fixed-bed system, the heat transfer area can be considered to be nearly the same for this comparison.

One difference between the condensers will be the temperature of the cooling water. Often cooling tower water is satisfactory to condense the steam from fixed-bed adsorbers. However, chilled cooling water is often needed in PURASIV HR systems to minimize the amount of VOC left in the recirculated nitrogen. Cooling tower water can be used, but the process design should be modified to increase the carbon rate through the system to provide more adsorption capacity in the secondary adsorber. This will maintain a VOC residual concentration that is low enough to sufficiently cleanse the carbon to maintain good effluent quality. Union Carbide's experience through has been that it is more cost effective to use chilled water in PURASIV HR systems handling low molecular weight solvents. However, the ability to modify the PURASIV HR process to account for the temperature of the condenser is another example of the flexibility available.

J. CAPITAL COSTS

Figure 7 presents installed capital costs (all in 1980 dollars) for "basic" vapor-phase adsorption systems as a function of flow rate. Installed costs for PURASIV HR systems were provided by Union Carbide. (17) Installed costs for fixed-bed systems were taken from a control device evaluation report for carbon

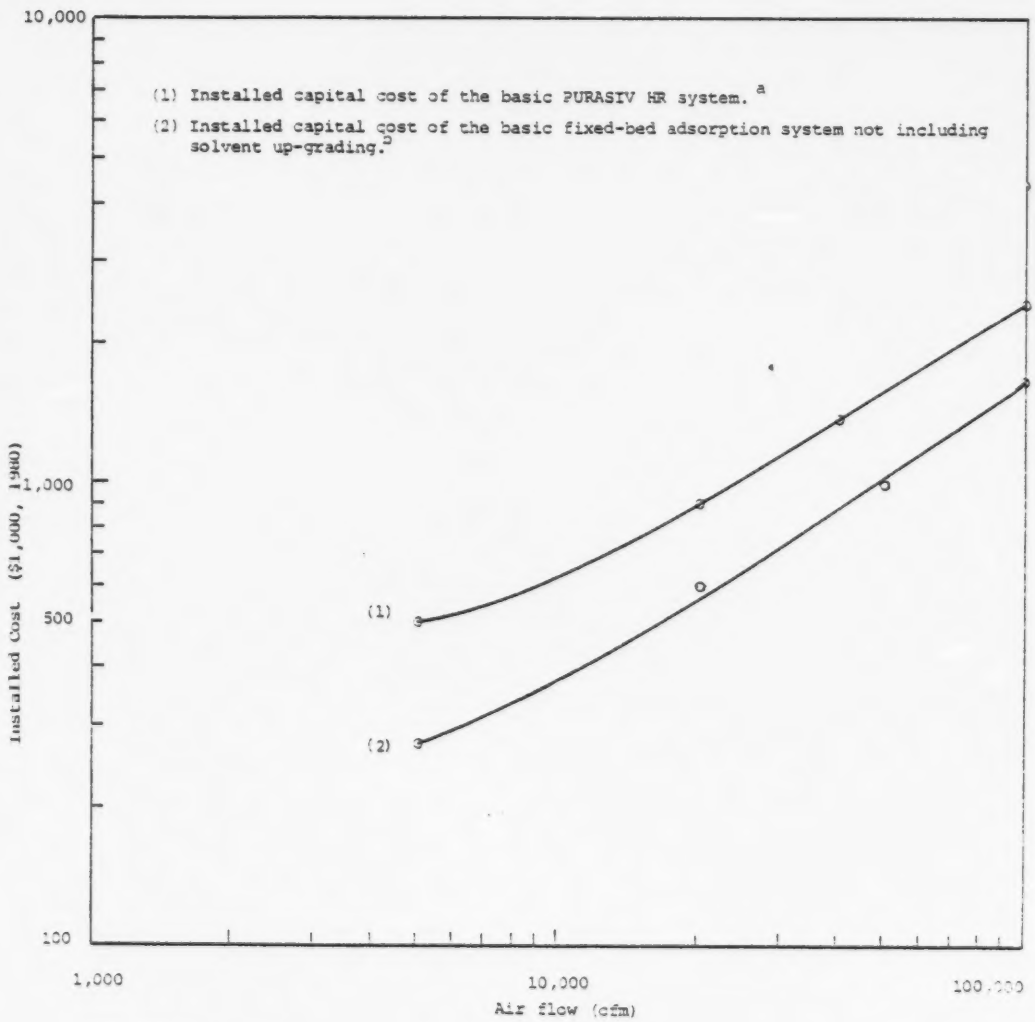


Figure 7. Comparison of Installed Costs of PURASIV HR Systems and Fixed-Bed Adsorption Systems

adsorption. (4) The cost data in Fig. 7 are for "basic" adsorption systems because they include only the battery limits costs of the adsorption equipment. They do not include costs for any auxiliary equipment that might be required for pretreatment of the inlet gas, wastewater treatment, or purification of the recovered solvent. The data in Fig. 7 show that the "basic" PURASIV HR systems have higher installed costs than "basic" fixed-bed systems.

It should not be concluded apriori that a "complete" PURASIV HR system will have higher installed costs than a "complete" fixed-bed system. An attempt was made to compare the installed costs of "complete" adsorption systems for both types. However, it was found that developing accurate cost data on truly comparable "complete" systems was very difficult and that a comparison of "complete" adsorption systems can only be done for specific cases. This is because the comparison is often influenced as much (or more) by the assumptions made about type and complexity of the auxiliary equipment as by the differences between the two types of adsorption systems.

K. OPERATING COSTS

The annual operating costs for a series of hypothetical adsorption systems were determined following the sample calculations outlined in Appendix D.

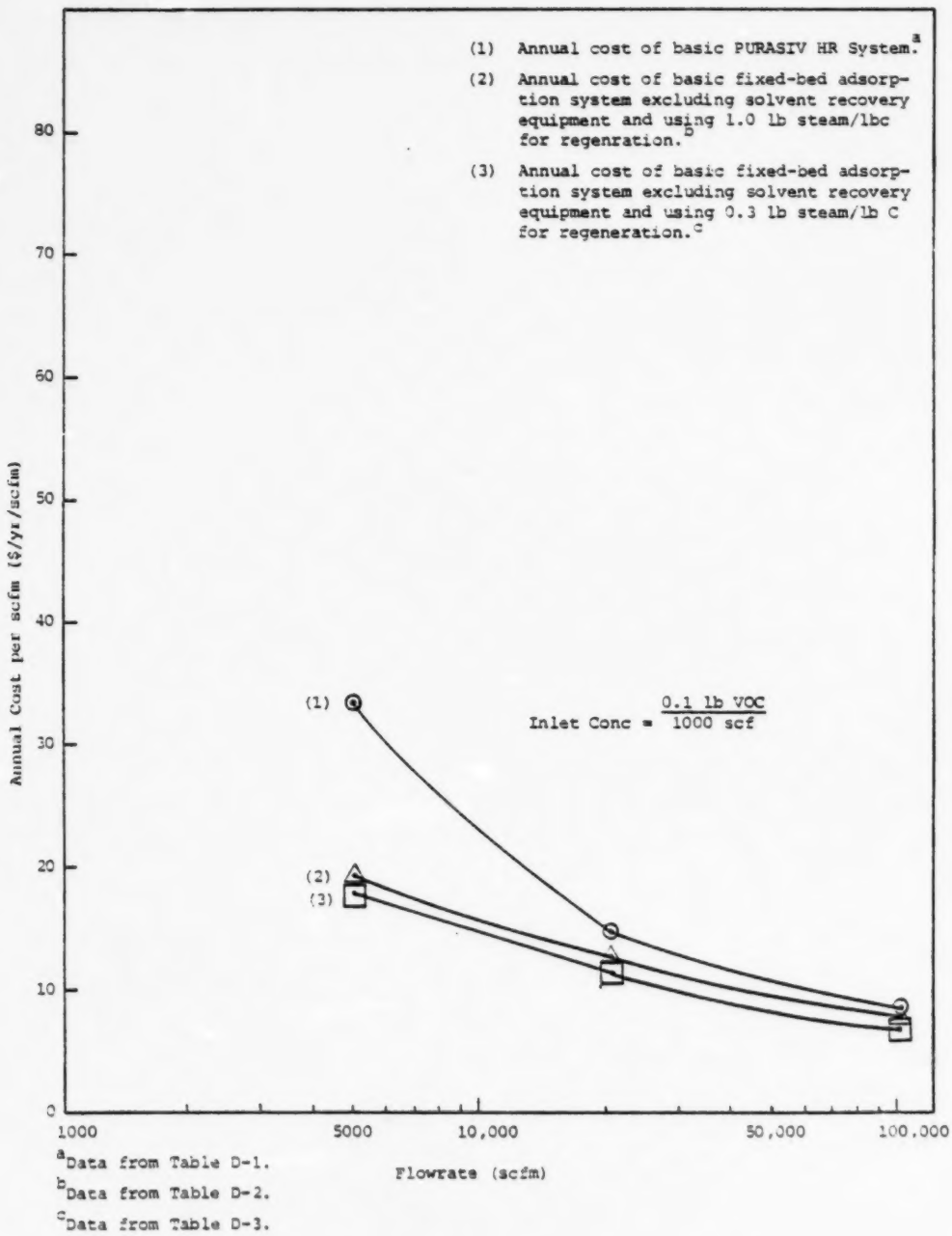
It was assumed for both types of adsorption systems that a working capacity of 0.10 lb VOC/lb carbon could be established. Labor costs were omitted because it was assumed that they would be the same for similar applications.

Values of parameters such as the consumption of steam, nitrogen, electricity, and carbon were selected based on the Polaroid PURASIV HR system. Two cases were developed for fixed-bed systems using similar data from the Control Device Evaluation Report for Carbon Adsorption. (4) The difference between the two fixed-bed cases was based on different values for steam consumption. One case using 1.0 lb steam/lb carbon for regeneration would be typical of fixed-bed systems designed to achieve high removal efficiencies. The other case using 0.3 lb steam/lb carbon for regeneration would be typical of most of the existing

fixed-bed systems that were designed primarily for recovery of vaporized solvents.

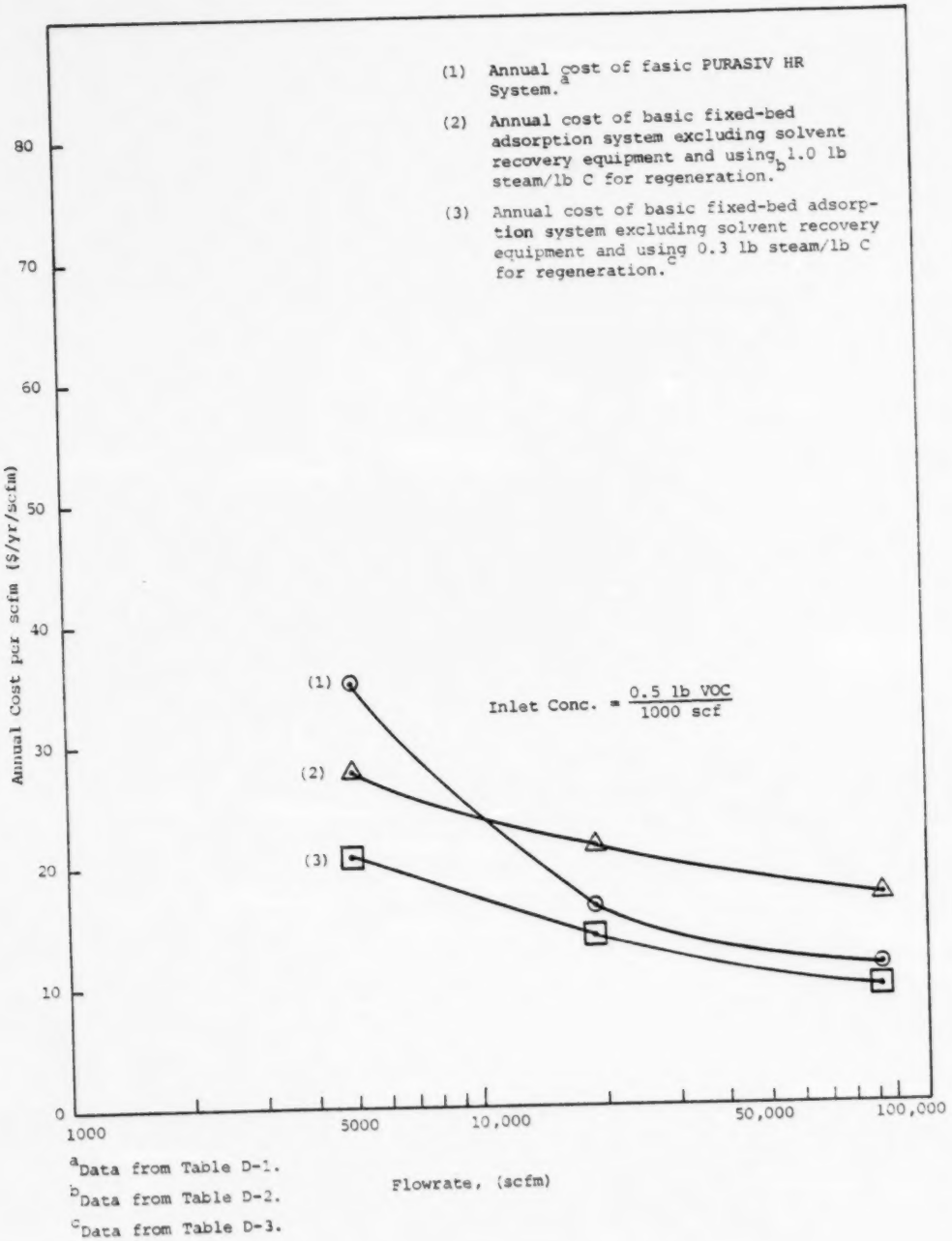
The results of these calculations are presented in Tables D-1, D-2, and D-3 in Appendix D. Figures 8, 9, 10, and 11 compare the annual costs of the adsorption systems in terms of $/yr-scfm versus flow rate at a series of inlet concentrations ranging from 0.1 lb VOC/1000 scf to 2.5 lb VOC/1000 scf. Inlet concentrations are expressed this way because these units allow calculation of carbon requirements without knowing the molecular weight of the hypothetical compounds. For a compound with a molecular weight of 80 lb/lb mole, the inlet concentration range noted above is equivalent to 450 ppm to 11,200 ppm. Since the inlet VOC concentration for many adsorption applications will be limited to 25% of the lower explosive limit, the majority of the potential applications of adsorption will fall in the region below 1.0 lb VOC/1000 scf. Cases in which the inlet VOC concentration exceeds 1.0 lb VOC/1000 scf will most often correspond to applications where the inlet VOC concentration is not limited by safety and/or insurance regulations.

Figures 8, 9, 10, and 11 each have three curves that correspond to the cost data in Tables D-1, D-2, and D-3. Curve 1 is for basic PURASIV HR systems, Curve 2 is for fixed-bed systems using 1.0 lb steam/lb carbon, and Curve 3 is for fixed-bed systems using 0.3 lb steam/lb carbon. The data in Figs. 8 through 11 illustrate several interesting concepts. First, it is evident that there is an economy of scale for both types of systems; i.e., one system to handle 20,000 cfm will be cheaper than four similar systems to handle 5000 cfm. Second, the progression from Fig. 8 through Fig. 11 shows that the annual costs for both types of adsorption systems (i.e., all three curves) increased with increasing inlet VOC concentration. This is because the variable costs for steam are directly related to the amount of VOC adsorbed. Note that the costs for the fixed-bed system using 1.0 lb steam/lb carbon (Curve 2) increased more with increasing inlet VOC concentration than the other two cases did (Curves 1 and 3).



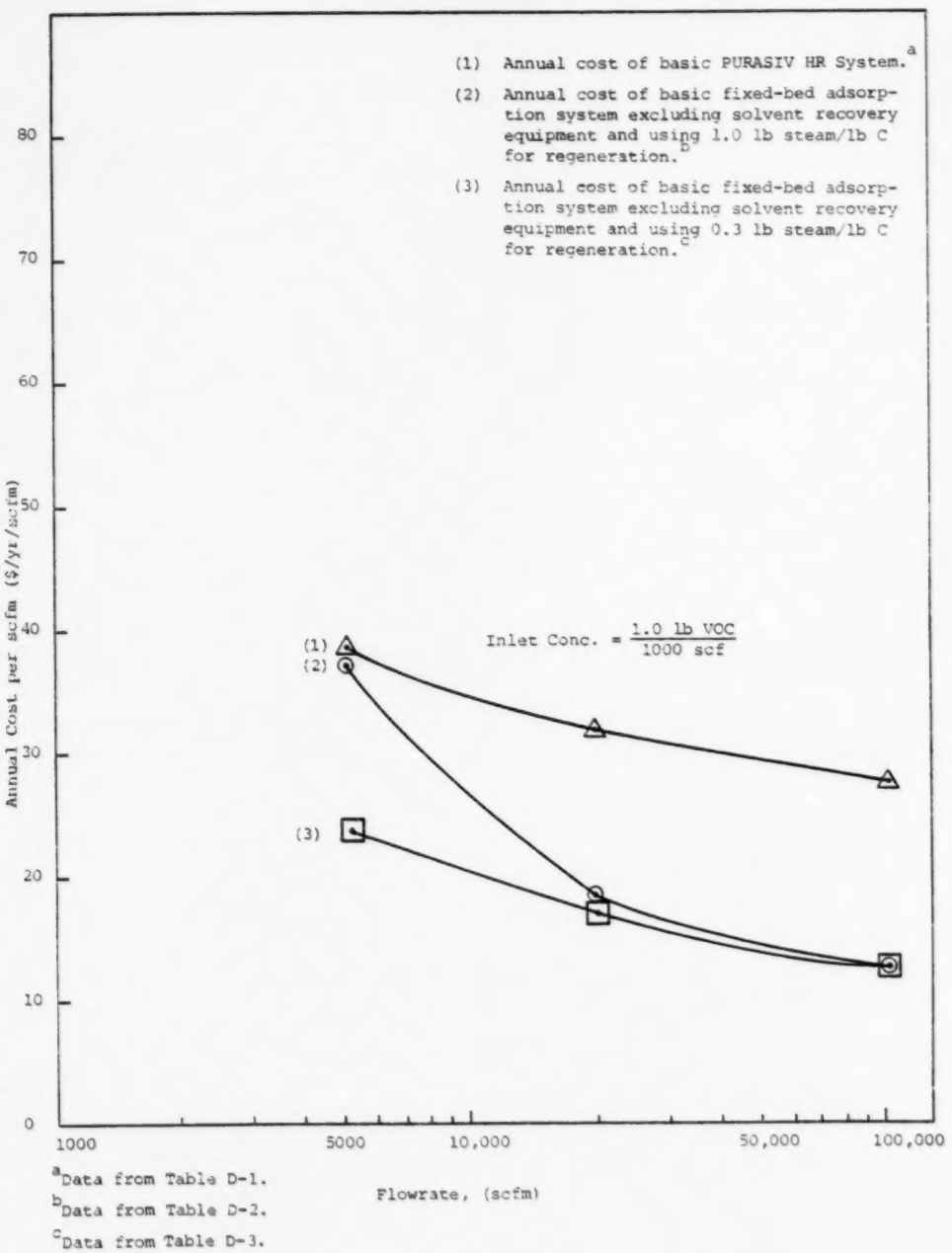
[a]Data from Table D-1.
[b]Data from Table D-2.
[c]Data from Table D-3.

Figure 8. Annual Cost per scfm vs Flowrate at Inlet Concentration = 0.1 lb VOC/1000 scf



[a]Data from Table D-1.
[b]Data from Table D-2.
[c]Data from Table D-3.

Figure 9. Annual Cost per scfm vs Flowrate at Inlet Concentration = 0.5 lb VOC/1000 scf



[a]Data from Table D-1.
[b]Data from Table D-2.
[c]Data from Table D-3.

Figure 10. Annual Cost per scfm vs Flowrate at Inlet Concentration = 1.0 lb VOC/1000 scf

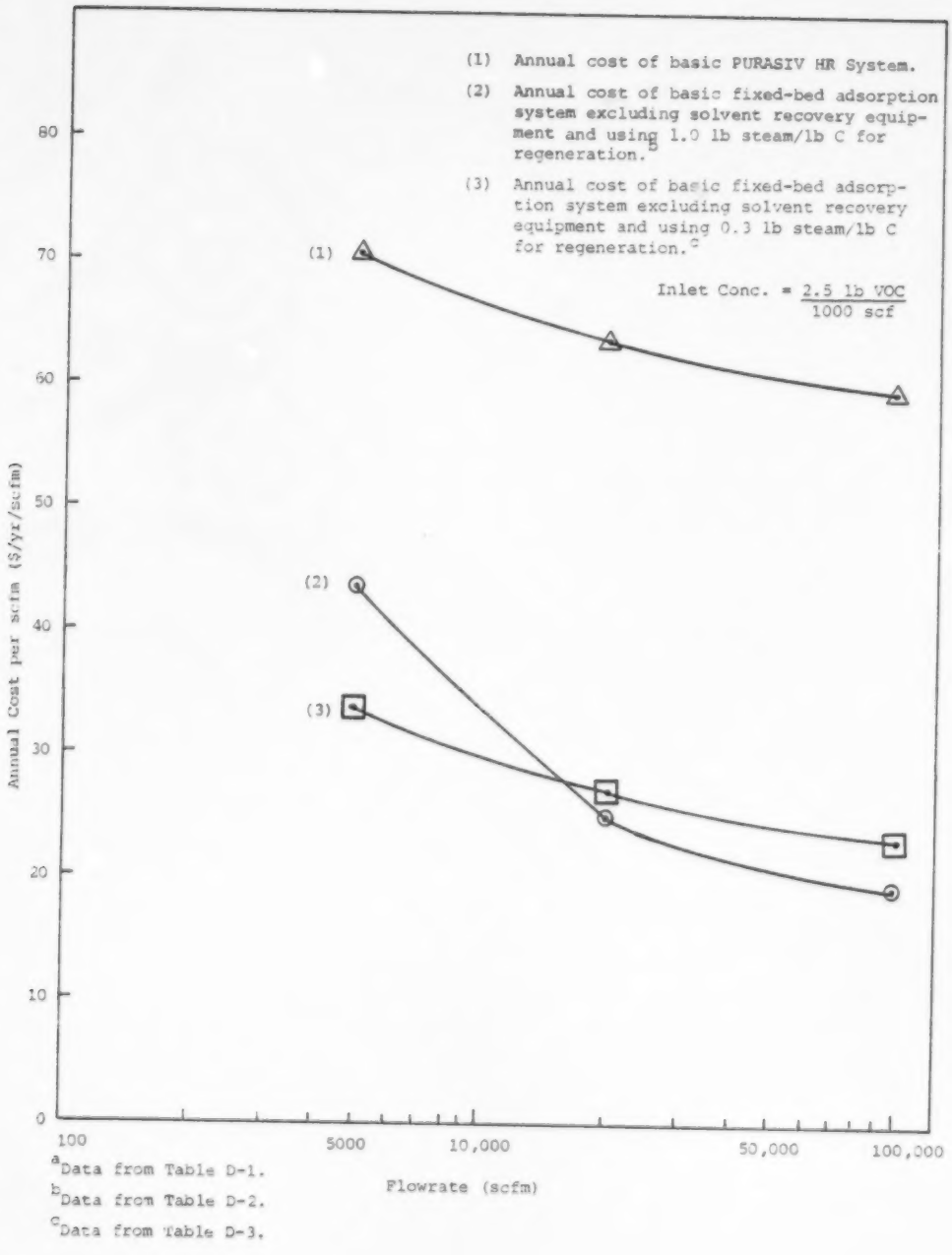


Figure 11. Annual Cost per scfm vs Flowrate at Inlet Concentration = 2.5 lb VOC/1000 scf

The overall result of this comparison between the costs of fixed-bed systems and PURASIV HR systems is that over a large portion of the range of flow rate and inlet VOC concentration considered, the differences between annual costs for the two types of adsorption systems are within the error bounds of the calculations. Significant differences between the annual costs existed only for the cases at the lowest flow rate (where costs for PURASIV HR systems were higher) and at inlet VOC concentrations above 0.5 lb VOC/1000 scf when 1.0 lb steam/lb carbon was needed for regeneration of fixed-bed systems (where costs for fixed-bed systems were higher).

Parity between the annual costs for the two types of systems is achieved because the higher fixed costs for the PURASIV HR systems (due to higher capital costs) are offset by higher variable costs for fixed-bed systems (due to higher steam consumption).

The significance of the conclusion that fixed-bed systems have higher costs under the conditions identified above must be tempered by two factors. First, in actual applications the variable costs for both types of systems would not increase as much with increasing inlet VOC concentration because the carbon loading capacity was assumed to be 0.1 lb VOC/lb carbon for all cases. If an allowance had been made for higher carbon loadings at higher inlet VOC concentrations, the differences between annual costs would not have increased with increasing inlet VOC concentrations as much because carbon consumption would not have increased as quickly.

Second, inlet VOC concentrations will be limited to ~1.0 lb VOC/1000 scf (by factors discussed previously in Section IV-D-2) for a majority of adsorption applications. Thus there will be a small number of adsorption applications where the large differences between costs for the two types of systems shown in Fig. 11 will be realized.

It is important to remember that the results of this generic comparison of the costs of hypothetical cases are a function of the assumptions that were made.

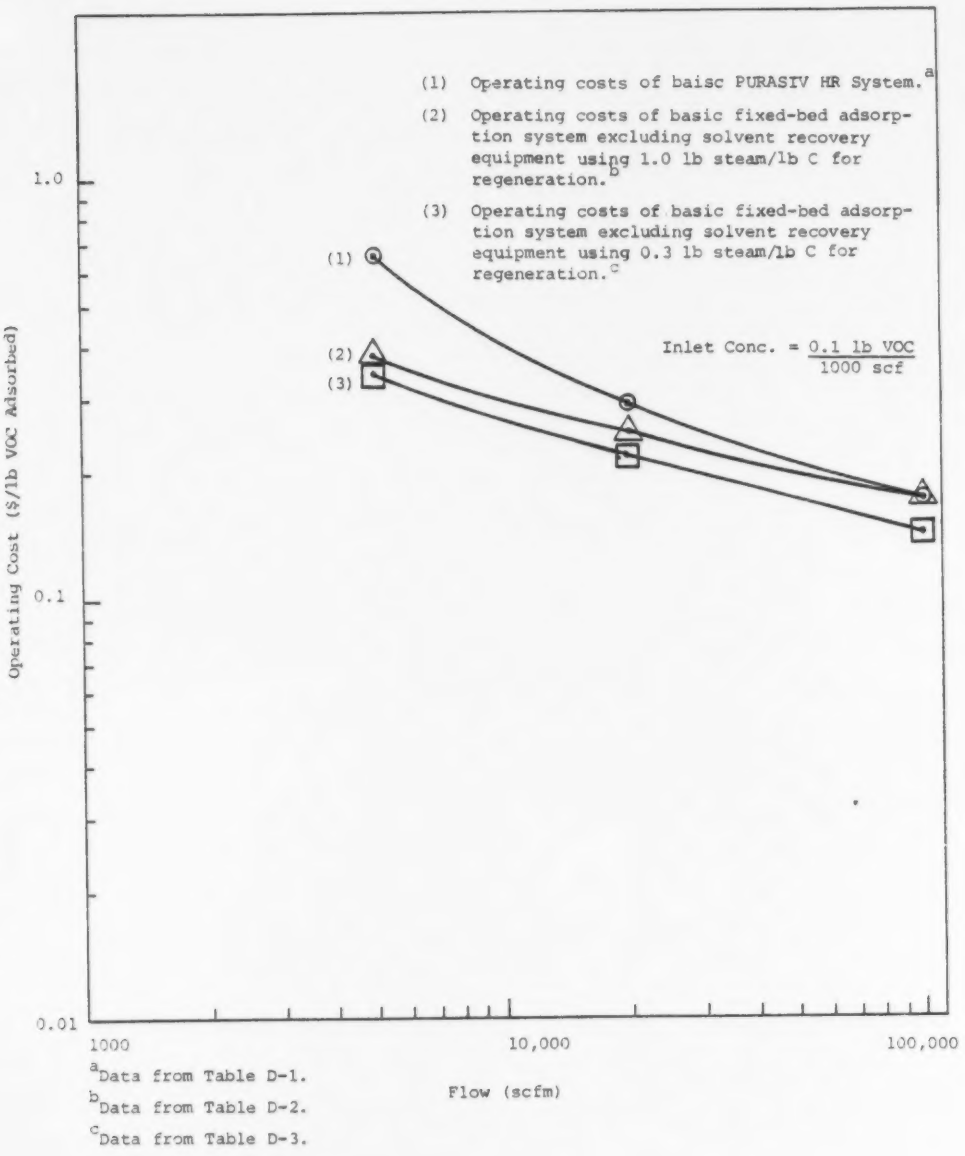
When a similar comparison is made for a specific case, consideration of site-specific factors may clearly show that one type of adsorption is less expensive than the other one. This is most likely to happen in situations where site specific factors effect the relative amount of steam required for regeneration or the relationship between the capital costs of the two systems. The relative steam requirements could be different if a higher loading capacity could be achieved for one type of system relative to the other one. The relationship between capital costs of the two systems would be changed if one type of system had a higher relative capital cost due to additional equipment for pretreatment, wastewater treatment, solvent recovery, or safety-related instrumentation.

L. COST EFFECTIVENESS

The cost effectiveness of both types of adsorption technologies can be evaluated generically by relating the annual costs to the amount of VOC that is adsorbed. The data in Tables D-1, D-2, and D-3 show that the cost effectiveness or annual cost/lb VOC adsorbed was affected very little by differences between outlet concentrations (50 ppm vs 10 ppm). Sample calculations are included in Appendix D.

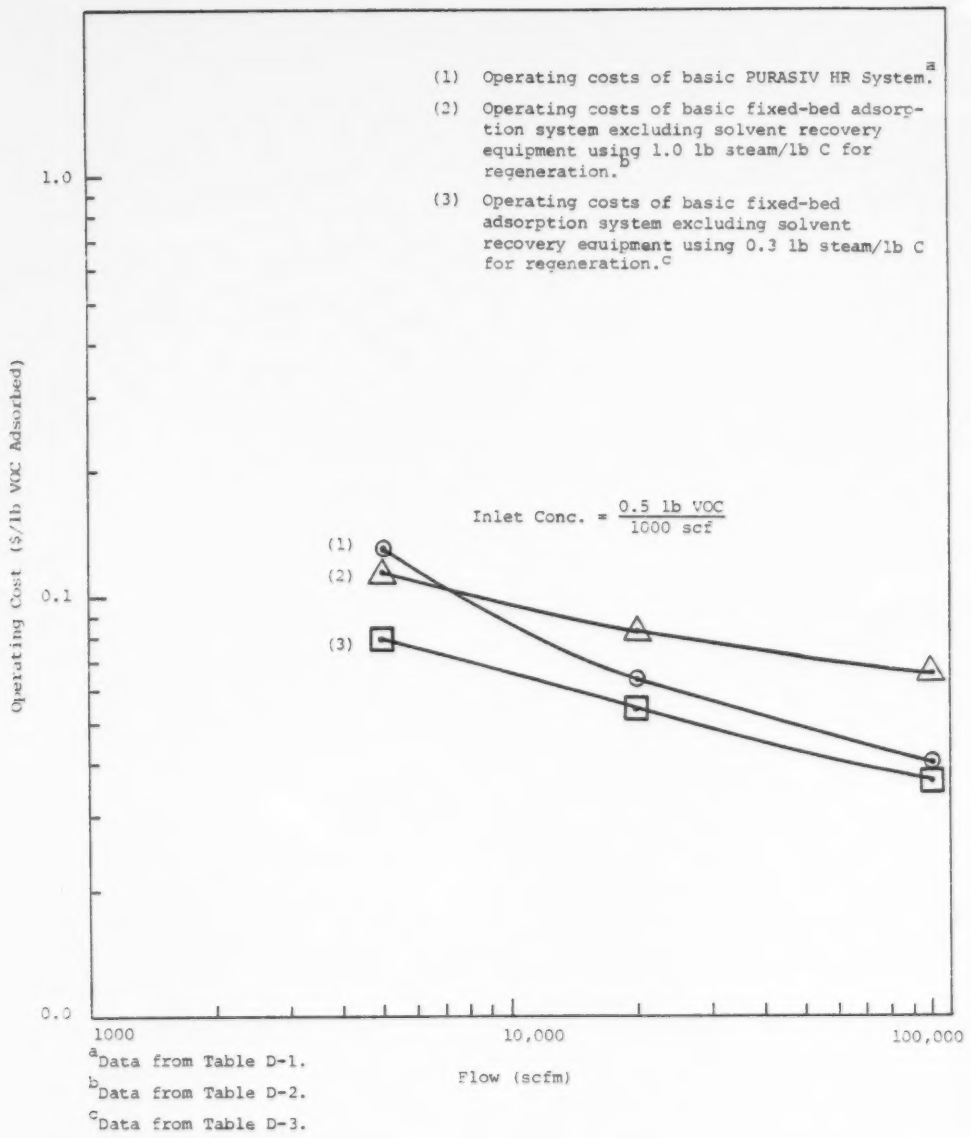
Figures 12 through 15 show the annual costs/lb VOC adsorbed vs flow rate for the same range of inlet concentrations as Figures 8 through 11. The data plotted in Figures 12 through 15 are taken from Tables D-1, D-2, and D-3 for outlet concentrations of 10 ppm. Figures 12 through 15 each have three curves that correspond to the three curves in Figures 8 through 11. Curve 1 is for the basic PURASIV HR systems, Curve 2 is for fixed-bed systems using 1.0 lb steam/lb carbon, and Curve 3 is for fixed-bed systems using 0.3 lb steam/lb carbon.

Figures 12 through 15 show that both types of adsorption systems can be cost effective when there are enough pounds of adsorbed VOC to give operating costs/lb VOC adsorbed that are competitive with the replacement values of many of the typical VOCs. The only cases where the annual costs/lb VOC adsorbed were higher than $0.20 to 0.40/lb VOC (replacement values of typical VOCs) were the cases for inlet concentration of 0.1 lb VOC/1000 scf and flow rates below 10,000 scfm (shown in Figure 12).


(1) Operating costs of baisc PURASIV HR System.[a]
(2) Operating costs of basic fixed-bed adsorption system excluding solvent recovery equipment using 1.0 lb steam/lb C for regeneration.[b]
(3) Operating costs of basic fixed-bed adsorption system excluding solvent recovery equipment using 0.3 lb steam/lb C for regeneration.[c]
Inlet Conc. = 0.1 lb VOC / 1000 scf
(1)
(2)
(3)
1.0
0.1
0.01
Operating Cost ($/lb VOC Adsorbed)
1000
10,000
100,000
Flow (scfm)

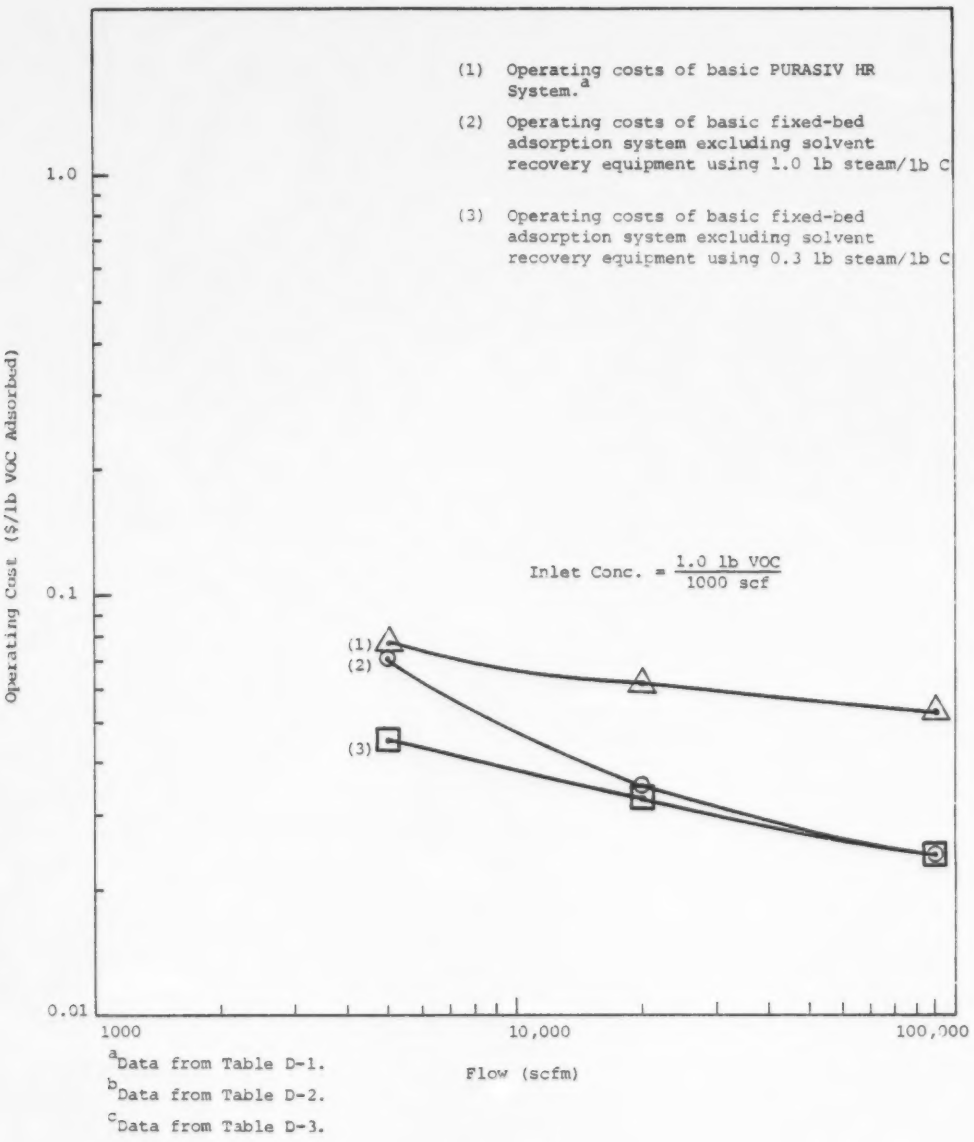
[a]Data from Table D-1.
[b]Data from Table D-2.
[c]Data from Table D-3.

Figure 12. Operating Costs per lb VOC Adsorbed vs. Flowrate; Inlet Concentration = 0.1 VOC/1000 scf


(1) Operating costs of basic PURASIV HR System.[a]
(2) Operating costs of basic fixed-bed adsorption system excluding solvent recovery equipment using 1.0 lb steam/lb C for regeneration.[b]
(3) Operating costs of basic fixed-bed adsorption system excluding solvent recovery equipment using 0.3 lb steam/lb C for regeneration.[c]
Inlet Conc. = 0.5 lb VOC / 1000 scf
Operating Cost ($/lb VOC Adsorbed)
1.0
0.1
0.0
1000
10,000
100,000
Flow (scfm)

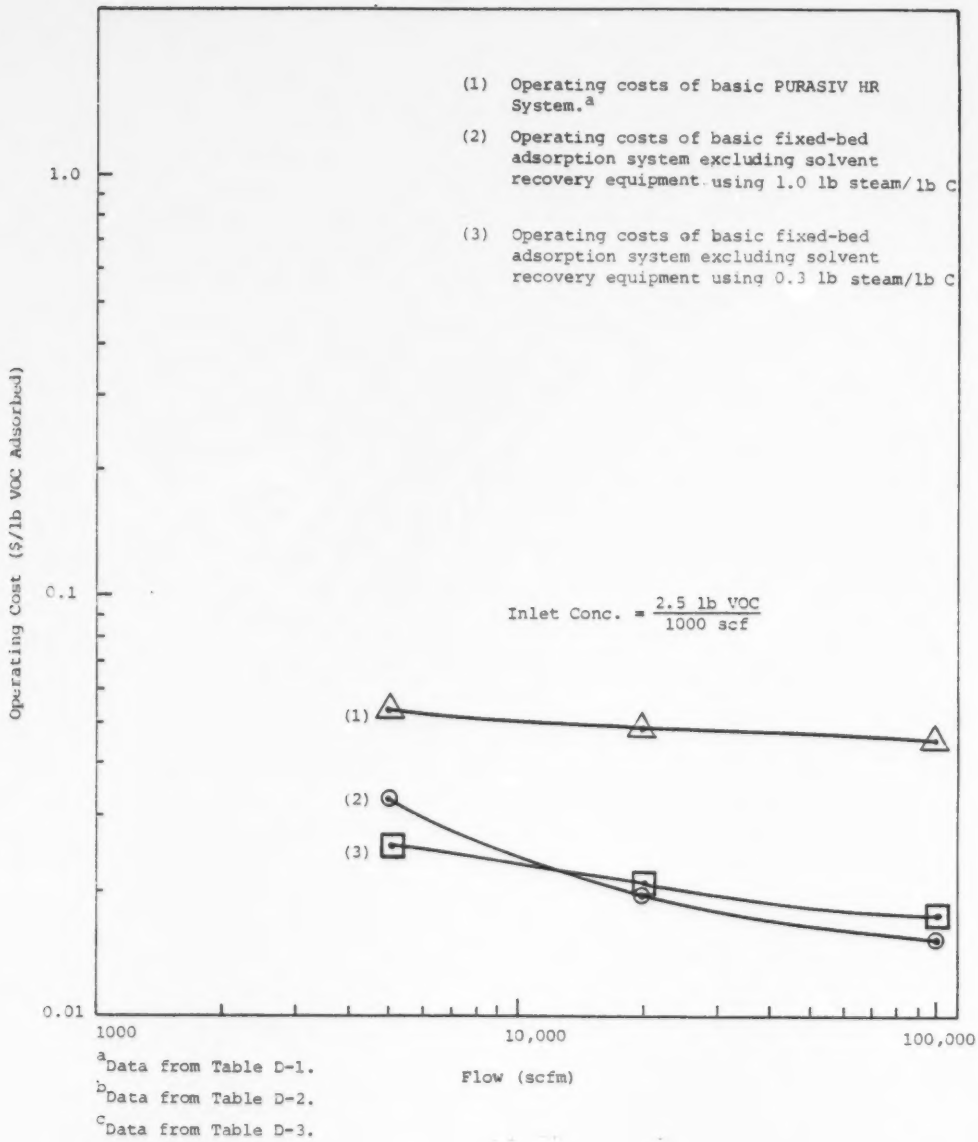
[a]Data from Table D-1.
[b]Data from Table D-2.
[c]Data from Table D-3.

Figure 13. Operating Costs per lb VOC Adsorbed vs. Flowrate; Inlet Concentration = 0.5 lb VOC/1000 scf


(1) Operating costs of basic PURASIV HR System.[a]
(2) Operating costs of basic fixed-bed adsorption system excluding solvent recovery equipment using 1.0 lb steam/lb C
(3) Operating costs of basic fixed-bed adsorption system excluding solvent recovery equipment using 0.3 lb steam/lb C
Inlet Conc. = 1.0 lb VOC / 1000 scf
Operating Cost ($/lb VOC Adsorbed)
1.0
0.1
0.01
(1)
(2)
(3)
1000
10,000
100,000
Flow (scfm)

[a]Data from Table D-1.
[b]Data from Table D-2.
[c]Data from Table D-3.

Figure 14. Operating Costs per lb VOC Adsorbed vs. Flowrate; Inlet Concentration = 1.0 lb VOC/1000 scf


(1) Operating costs of basic PURASIV HR System.[a]
(2) Operating costs of basic fixed-bed adsorption system excluding solvent recovery equipment using 1.0 lb steam/lb C
(3) Operating costs of basic fixed-bed adsorption system excluding solvent recovery equipment using 0.3 lb steam/lb C
Inlet Conc. = 2.5 lb VOC / 1000 scf
Operating Cost ($/lb VOC Adsorbed)
1.0
0.1
0.01
(1)
(2)
(3)
1000
10,000
100,000
Flow (scfm)

[a]Data from Table D-1.
[b]Data from Table D-2.
[c]Data from Table D-3.

Figure 15. Operating Costs per lb VOC Adsorbed vs. Flowrate; Inlet Concentration = 2.5 lb VOC/1000 scf

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APPENDIX A

SAMPLING AND ANALYTICAL PLAN FOR PURASIV HR SYSTEM AT POLAROID CORPORATION

If a copy of this Appendix is required, it can be obtained from:

Ronald J. Turner
Industrial Pollution Control Division
Industrial Environmental Research Laboratory
Cincinnati, Ohio 45268

APPENDIX B

SAMPLE CHROMATOGRAMS FROM FIELD TESTS
MAY 31, 1980

If a copy of this Appendix is required, it can be obtained from:

Ronald J. Turner
Industrial Pollution Control Division
Industrial Environmental Research Laboratory
Cincinnati, Ohio 45268

APPENDIX C

EXCERPTS FROM TWO GENERAL MOTORS' REPORTS TO EPA REGION IX

ON PURASIV HR SYSTEM

If a copy of this Appendix is required, it can be obtained from:

Ronald J. Turner
Industrial Pollution Control Division
Industrial Environmental Research Laboratory
Cincinnati, Ohio 45268

APPENDIX D

ANNUAL COST CALCULATIONS

If a copy of this Appendix is required, it can be obtained from:

Ronald J. Turner
Industrial Pollution Control Division
Industrial Environmental Research Laboratory
Cincinnati, Ohio 45268